

Gray, Hurst, Lewis, and Meyer

SOLUTIONS MANUAL TO ACCOMPANY

Analysis and Design of
ANALOG INTEGRATED CIRCUITS

Prepared by

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FOURTH EDITION

Solutions Manual to Accompany

Analysis and Design
of Analog
Integrated Circuits
Fourth Edition

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John Wiley & Sons, Inc.
New York · Chichester · Brisbane · Toronto · Singapore

CHAPTER 1

1.1

(a) From (1.1) the built-in potential

$$\begin{aligned} \psi_0 &= V_T \ln \frac{N_A N_D}{n_i^2} \\ &= 26 \ln \frac{8 \times 10^{15} \times 10^{17}}{2.25 \times 10^{20}} = 751 \text{ mV} \end{aligned}$$

From (1.14) the depletion-layer depth in the p-type region is,

$$\begin{aligned} W_1 &= \left[\frac{2 \times 1.04 \times 10^{-12} \times 5.75}{1.6 \times 10^{-19} \times 8 \times 10^{15} (1 + 0.08)} \right]^{1/2} \\ &= 0.93 \text{ } \mu\text{m} \end{aligned}$$

In the n-type region using (1.15)

$$\begin{aligned} W_2 &= \left[\frac{2 \times 1.04 \times 10^{-12} \times 5.75}{1.6 \times 10^{-19} \times 10^{17} \times 13.5} \right]^{1/2} \\ &= 0.074 \text{ } \mu\text{m} \end{aligned}$$

From (1.7) the maximum field is

$$\begin{aligned} E_{\text{MAX}} &= -q \frac{N_A}{\epsilon} W_1 \\ &= -1.6 \times 10^{-19} \times \frac{8 \times 10^{15} \times 0.93 \times 10^{-4}}{1.04 \times 10^{-12}} \\ &= -11.4 \times 10^4 \text{ V/cm} \end{aligned}$$

(b) For zero volts bias,

$$\psi_0 + V_R = \psi_0 = 0.75$$

$$W_1 = 0.93 \sqrt{\frac{0.75}{5.75}} = 0.34 \text{ } \mu\text{m}$$

$$W_2 = 0.074 \sqrt{\frac{0.75}{5.75}} = 0.027 \text{ } \mu\text{m}$$

$$\begin{aligned} E_{\text{MAX}} &= -11.4 \times 10^4 \times \frac{0.34}{0.93} \\ &= -4.17 \times 10^4 \text{ V/cm} \end{aligned}$$

For 0.3V forward bias,

$$\psi_0 + V_R = 0.45 \text{ V}$$

$$W_1 = 0.93 \sqrt{\frac{0.45}{5.75}} = 0.26 \text{ } \mu\text{m}$$

$$W_2 = 0.074 \sqrt{\frac{0.45}{5.75}} = 0.021 \text{ } \mu\text{m}$$

$$\begin{aligned} E_{\text{MAX}} &= -11.4 \times 10^4 \times \frac{0.26}{0.93} \\ &= -3.19 \times 10^4 \text{ V/cm} \end{aligned}$$

1.2

From (1.20), the zero bias junction capacitance is,

$$\begin{aligned} C_{j0} &= A \left[\frac{q \epsilon N_A N_D}{2(N_A + N_D)} \right]^{1/2} \frac{1}{\sqrt{\psi_0}} \\ &= 2 \times 10^{-5} \times \left[\frac{1.6 \times 10^{-19} \times 1.04 \times 10^{-12} \times 8 \times 10^{15} \times 10^{17}}{2(8 \times 10^{15} + 10^{17})} \right]^{1/2} \\ &\quad \times \frac{1}{\sqrt{0.75}} \end{aligned}$$

$$= 0.57 \text{ pF}$$

Using (1.20) with $V_D = -5\text{V}$ we obtain,

$$C_j = \frac{C_{j0}}{\sqrt{7.7}} = 0.2 \text{ pF}$$

with $V_D = 0.3\text{V}$

$$C_j = \frac{C_{j0}}{\sqrt{0.6}} = 0.74 \text{ pF}$$

1.3

The break down voltage can be calculated from (1.24) using

$$|E_{MAX}| = E_{CRIT} = 4 \times 10^5 \text{ V/cm}$$

Thus,

$$4 \times 10^5 = \left[\frac{2 \times 1.6 \times 10^{-19} \times 8 \times 10^{15} \times 10^{17} \times V_R}{1.04 \times 10^{-12} (8 \times 10^{15} + 10^{17})} \right]^{1/2}$$

$$\therefore V_R = 70.2 \text{ V}$$

From (1.81),

$$BV_{CEO} = \frac{48.8}{\sqrt[4]{200}} = 13 \text{ V}$$

1.6

$$BV_{CBO} = \frac{1.04 \times 10^{-12}}{3.2 \times 10^{-19} \times 10^{15}} \times 9 \times 10^{10} = 293 \text{ V}$$

$$BV_{CEO} = \frac{293}{\sqrt[4]{400}} = 65.5 \text{ V}$$

1.4

Junction curvature causes (1.24) to become

$$|E_{MAX}| = 1.5 \left[\frac{2q N_A N_D V_R}{\epsilon (N_A + N_D)} \right]^{1/2}$$

If $N_A \gg N_D$, $|E_{MAX}| = 3 \times 10^5 \text{ V/cm}$ and $V_R = 150 \text{ V}$, then this equation gives

$$9 \times 10^{10} = 2.25 \frac{2q N_D V_R}{\epsilon}$$

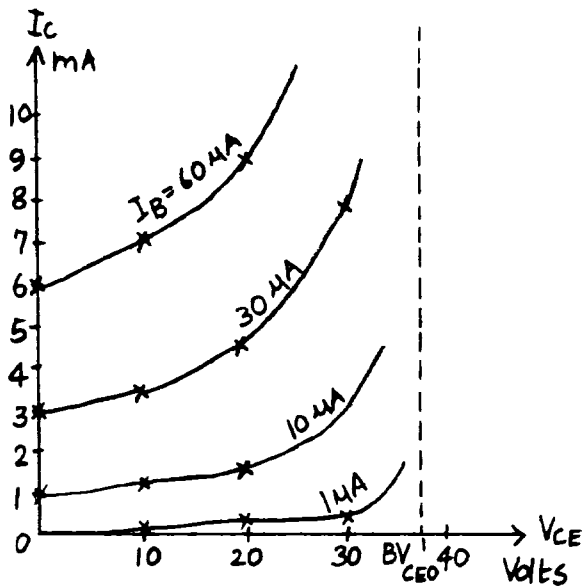
$$\begin{aligned} \therefore N_D &= \frac{9 \times 10^{10} \times 1.04 \times 10^{-12}}{3.2 \times 10^{-19} \times 150 \times 2.25} \\ &= 8.7 \times 10^{14} \text{ atoms/cm}^3 \end{aligned}$$

1.5

The plane breakdown voltage is

$$\begin{aligned} BV_{CBO} &= \frac{\epsilon (N_A + N_D)}{2q N_A N_D} E_{CRIT}^2 \\ &= \frac{1.04 \times 10^{-12}}{3.2 \times 10^{-19} \times 6 \times 10^{15}} \times 9 \times 10^{10} = 48.8 \text{ V} \end{aligned}$$

1.7 (a)



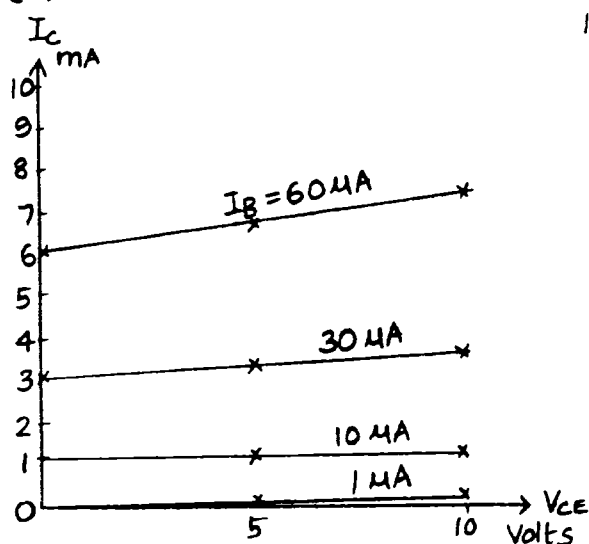
$$I_C = \left(1 + \frac{V_{CE}}{V_A}\right) \frac{M \alpha_F}{1 - M \alpha_F} I_B$$

$$M = \frac{1}{1 - \left(\frac{V_{CB}}{BV_{CBO}}\right)^n}$$

Where $\alpha_F = 0.99$, $V_A = 50V$

$BV_{CBO} = 120V$, $n = 4$

1.8 (b)



1.8

$$g_m = \frac{I_C}{V_T} = \frac{0.2 \text{ mA}}{26 \text{ mV}} = 7.69 \frac{\text{mA}}{\text{V}}$$

$$r_o = \frac{1}{\eta g_m} = \frac{1}{10^{-3} (7.69 \text{ m})} = 130 \text{ k}\Omega$$

$$r_{\pi} = \frac{\beta_o}{g_m} = \frac{100}{7.69 \text{ m}} = 13 \text{ k}\Omega$$

$$C_b = \tau_F g_m = (15 \text{ ps}) (7.69 \text{ m}) = 115 \text{ fF}$$

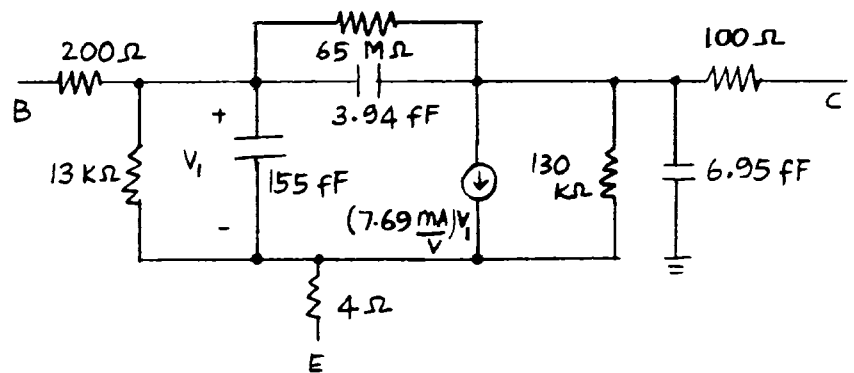
$$r_{\mu} = 5 \beta_o r_o = 5 (100) (130 \text{ k}) = 65 \text{ M}\Omega$$

$$C_{je} = 2 C_{jeo} = 40 \text{ fF}$$

$$C_{\mu} = \frac{C_{\mu o}}{\sqrt{1 + \frac{V_{CB}}{\Psi_o}}} = \frac{10 \text{ fF}}{\sqrt{1 + \frac{3}{0.55}}} = 3.94 \text{ fF}$$

$$C_{cs} = \frac{C_{cs o}}{\sqrt{1 + \frac{V_{cs}}{\Psi_o}}} = \frac{20 \text{ fF}}{\sqrt{1 + \frac{4}{0.55}}} = 6.95 \text{ fF}$$

$$C_{\pi} = C_b + C_{je} = 155 \text{ fF}$$



1.9

$$g_m = \frac{I_c}{V_T} = \frac{1 \text{ mA}}{26 \text{ mV}} = 38.5 \frac{\text{mA}}{\text{V}}$$

$$r_o = \frac{1}{\eta g_m} = \frac{1}{10^{-3} (38.5 \text{ m})} = 26 \text{ k}\Omega$$

$$r_{\pi} = \frac{\beta_o}{g_m} = \frac{100}{38.5 \text{ m}} = 2.6 \text{ k}\Omega$$

$$C_b = \tau_F g_m = (15 \text{ ps})(38.5 \text{ m}) = 577 \text{ fF}$$

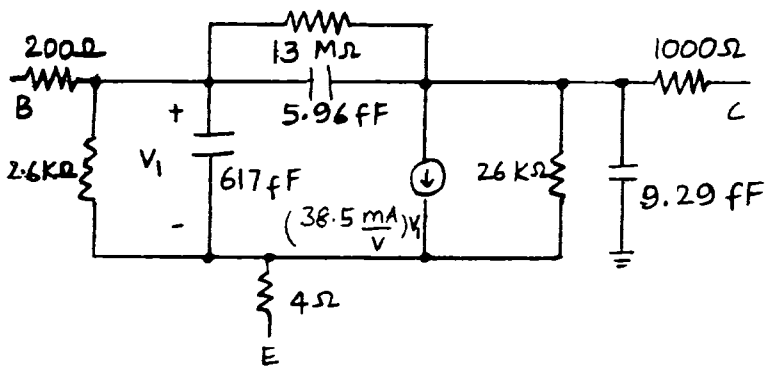
$$r_M = 5 \beta_o r_o = 5(100)(26 \text{ k}) = 13 \text{ M}\Omega$$

$$C_{je} \approx 2 C_{je0} = 40 \text{ fF}$$

$$C_M = \frac{C_{M0}}{\sqrt{1 + \frac{V_{CB}}{\psi_o}}} = \frac{10 \text{ fF}}{\sqrt{1 + \frac{1}{0.55}}} = 5.96 \text{ fF}$$

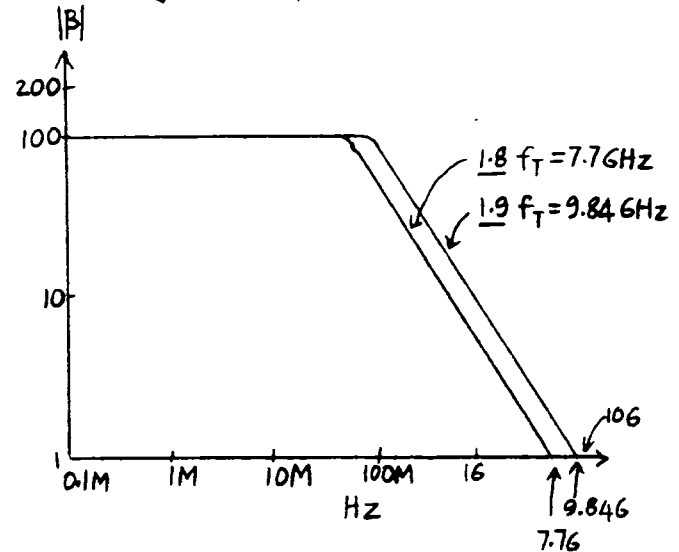
$$C_{cs} = \frac{C_{cs0}}{\sqrt{1 + \frac{V_{cs}}{\psi_o}}} = \frac{20 \text{ fF}}{\sqrt{1 + \frac{2}{0.55}}} = 9.29 \text{ fF}$$

$$C_{\pi} = C_b + C_{je} = 617 \text{ fF}$$



For problem (1.9),

$$\beta(j\omega) = \frac{38.5 \text{ mA/V}}{j\omega 623 \text{ fF}} = \frac{61.86}{j\omega} = \frac{9.846}{jf}$$

1.10 At high frequencies,

$$\beta(j\omega) = \frac{\omega_T}{j\omega} = \frac{g_m}{j\omega(C_M + C_{\pi})}$$

For problem (1.8)

$$\beta(j\omega) = \frac{7.69 \text{ mA/V}}{j\omega 159 \text{ fF}} = \frac{48.46}{j\omega} = \frac{7.76}{jf}$$

1.11

(a) At $I_C = 1 \text{ mA}$, $\tau_{T_1} = \frac{1}{2\pi f_{T_1}} = \frac{1}{2\pi \cdot 600 \times 10^6}$
 $= 0.265 \text{ ns}$

At $I_C = 10 \text{ mA}$, $\tau_{T_2} = \frac{1}{2\pi f_{T_2}} = \frac{1}{2\pi \times 10^9}$
 $= 0.159 \text{ ns}$

$\therefore 265 = \tau_F + 26 \times (C_M + C_{je})$

$159 = \tau_F + 2.6 \times (C_M + C_{je})$

$\therefore 106 = 23.4 (C_M + C_{je})$

$\therefore C_M + C_{je} = 4.53 \text{ pF}$

$\tau_F = 147 \text{ ps}$

Since $C_M \approx 0.15 \text{ pF}$, $C_{je} = 4.4 \text{ pF}$

$I_C = 0.1 \text{ mA}$

$g_m = \frac{0.1 \times 10^{-3}}{26 \times 10^{-3}} = 3.8 \text{ mA/V}$

$r_{\pi} = \frac{100}{3.8} \text{ k}\Omega = 26 \text{ k}\Omega$

$r_o = 500 \text{ k}\Omega$

$r_M = 5 \times 100 \times 500 \text{ k}\Omega = 250 \text{ M}\Omega$

$C_b = \tau_F g_m = 0.147 \times 10^{-9} \times 3.8 \times 10^{-3}$
 $= 0.56 \text{ pF}$

$C_{\pi} = 0.56 + 4.4 = 5.0 \text{ pF}$

$C_M = 0.15 \sqrt{\frac{1 + \frac{10}{0.55}}{1 + \frac{2}{0.55}}} = 0.31 \text{ pF}$

$C_{cs} = 1 \sqrt{\frac{1 + \frac{10}{0.55}}{1 + \frac{15}{0.55}}} = 0.82 \text{ pF}$

$r_b = 100 \Omega$, $r_c = 100 \Omega$

$I_C = 1 \text{ mA}$

$g_m = \frac{1}{26} = 38 \text{ mA/V}$

$r_{\pi} = \frac{100}{38} \text{ k}\Omega = 2.6 \text{ k}\Omega$

$r_o = 50 \text{ k}\Omega$, $r_M = 25 \text{ M}\Omega$

$C_b = 5.6 \text{ pF}$

$C_{\pi} = 5.6 + 4.4 = 10 \text{ pF}$

$C_M = 0.31 \text{ pF}$, $C_{cs} = 0.82 \text{ pF}$

$r_b = 100 \Omega$, $r_c = 100 \Omega$

$I_C = 5 \text{ mA}$

$g_m = 190 \text{ mA/V}$

$r_{\pi} = \frac{100}{190} = 530 \Omega$

$r_o = 10 \text{ k}\Omega$, $r_M = 5 \text{ M}\Omega$

$C_b = 28 \text{ pF}$

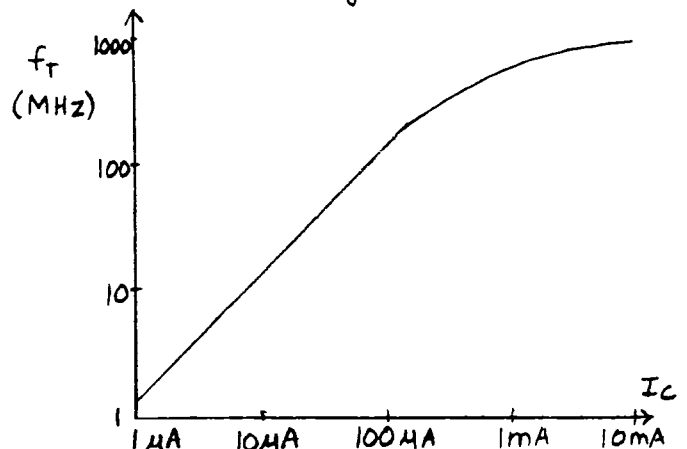
$C_{\pi} = 28 + 4.4 = 32.4 \text{ pF}$

$C_M = 0.31 \text{ pF}$, $C_{cs} = 0.82 \text{ pF}$

$r_b = 100 \Omega$, $r_c = 100 \Omega$

(b) $f_T = \frac{1}{2\pi} \frac{g_m}{C_b + C_{je} + C_M}$
 $= \frac{1}{2\pi} \frac{1}{\tau_F + \frac{V_T}{I_C} (C_{je} + C_M)}$

$\tau_F = 0.147 \text{ ns}$, $C_{je} + C_M = 4.7 \text{ pF}$



1.12

$$(a) \tau_F = \frac{W_B^2}{2D_p} = \frac{10^{-6}}{26} = 38.5 \text{ ns}$$

$$f_T = \frac{1}{2\pi} \frac{g_m}{C_b + C_{je}}$$

$$= \frac{1}{2\pi} \frac{1}{\tau_F + \frac{V_T C_{je}}{I_C}}$$

$$= \frac{1}{2\pi} \frac{1}{38.5 + 0.1} \times 10^9 = 4.1 \text{ MHz}$$

$$Q = C_F I_c = 38.5 \times 10^{-9} \times 0.5 \times 10^{-3} \\ = 19.3 \text{ pC}$$

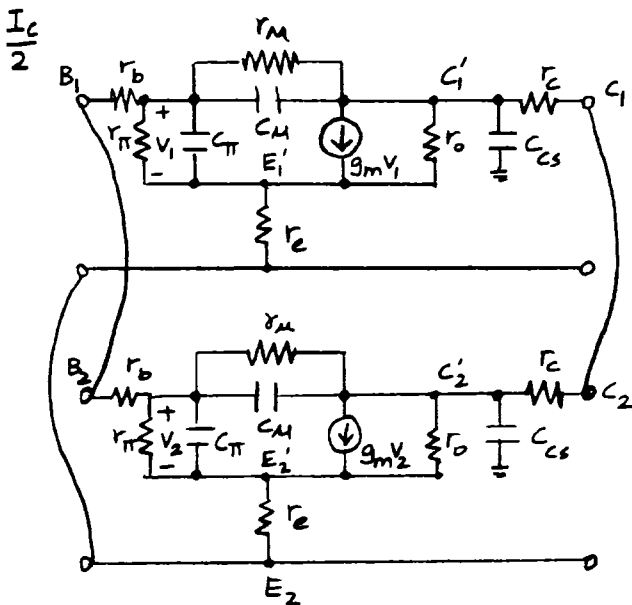
$$(b) \frac{\Delta I_C}{I_C} = \frac{\Delta W_B}{W_B} = \frac{0.1}{10} \text{ per volt of } V_{CE}$$

$$\therefore \Delta I_C = 0.5 \times \frac{1}{100} \text{ mA per volt of } V_{CE}$$

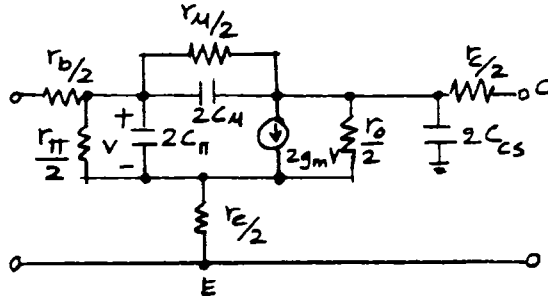
$$\therefore r_o = \frac{\Delta V_{CE}}{\Delta I_C} = \frac{100}{0.5} \text{ K}\Omega = 200 \text{ K}\Omega$$

1.13

connect two transistors in parallel,
each with a collector bias current



Points B'_1 and B'_2 will be at the same potential and can be connected. Also C'_1 and C'_2 , E'_1 and E'_2 . Thus, the composite device becomes as shown with a collector bias current I_C .

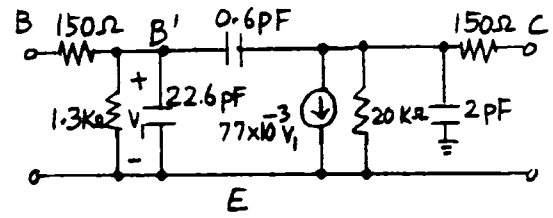


Since R_b , R_c and R_e are assumed constant, the values of these resistors are halved in the composite device as compared to the original device at the same total current.

Since C_M and C_{CS} are independent of bias current, the values of these capacitors are doubled in the composite device. Since r_{π} , r_o and r_M are proportional to $1/I_C$, the values of these resistors are unchanged in the composite device as compared to the original device with the same total current. Since g_m is proportional to I_C , its value is unchanged in the composite device.

Finally, $C_{\pi} = C_{je} + C_b$ where C_{je} is assumed constant and C_b is proportional to I_C . Thus, in the composite device, C_{je} is doubled and C_b is unchanged.

As a consequence, C_{π} in the composite is larger than in the original device at the same total current, but the increase in C_{π} is less than two times.



1.14

Since current gain is 9 at 50 MHz,

$$f_T = 9 \times 50 = 450 \text{ MHz at } \underline{I_C = 1 \text{ mA}}$$

$$\therefore \tau_T = \frac{1}{2\pi f_T} = 0.354 \text{ ns}$$

From (1.130),

$$\tau_T = \tau_F + \frac{C_{je} + C_u}{g_m}$$

$$\therefore 0.354 = 0.25 + (C_{je} + C_u) \times 26$$

$$\therefore C_{je} + C_u = 4 \text{ pF}$$

$$\text{Given } C_u = 0.6 \text{ pF}, \therefore C_{je} = 3.4 \text{ pF}$$

At $\underline{I_C = 2 \text{ mA}}$

$$C_b = \tau_F g_m = 0.25 \times 10^{-9} \times \frac{1}{13} = 19.2 \text{ pF}$$

$$\therefore C_{\pi} = C_{je} + C_b = 3.4 + 19.2 = 22.6 \text{ pF}$$

$$g_m = \frac{1}{13} = 77 \text{ mA/V}$$

$$r_o = \frac{V_A}{I_C} = \frac{40}{2} \text{ k}\Omega = 20 \text{ k}\Omega$$

$$r_{\pi} = \frac{\beta_o}{g_m} = 1300 \Omega$$

1.15

$$(a) \frac{\mu_n'}{2} \frac{W}{L} = 97 \times 10 = 970 \text{ } \mu\text{A/V}^2$$

so in triode region,

$$I_D = 970 [2(V_{GS} - 0.6)V_{DS} - V_{DS}^2] \text{ } \mu\text{A}$$

In active region (saturation),

$$I_D = 970 (V_{GS} - 0.6)^2 (1 + 0.024 V_{DS}) \text{ } \mu\text{A}$$

(b) From (1.140),

$$V_t = V_{t0} + \gamma (\sqrt{2\phi_F + V_{SB}} - \sqrt{2\phi_F})$$

From (1.141),

$$\gamma = \frac{\sqrt{2q\epsilon N_A}}{C_{ox}} = \frac{\sqrt{2 \times 1.6 \times 10^{-19} \times 1.04 \times 10^{12} \times 5 \times 10^{15}}}{4.3 \times 10^{-7}} = 0.094 \sqrt{\text{V}}$$

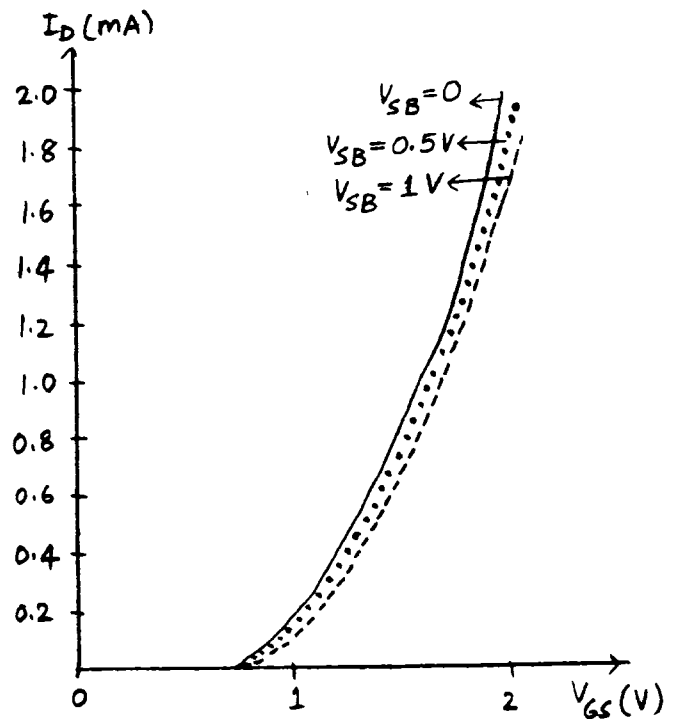
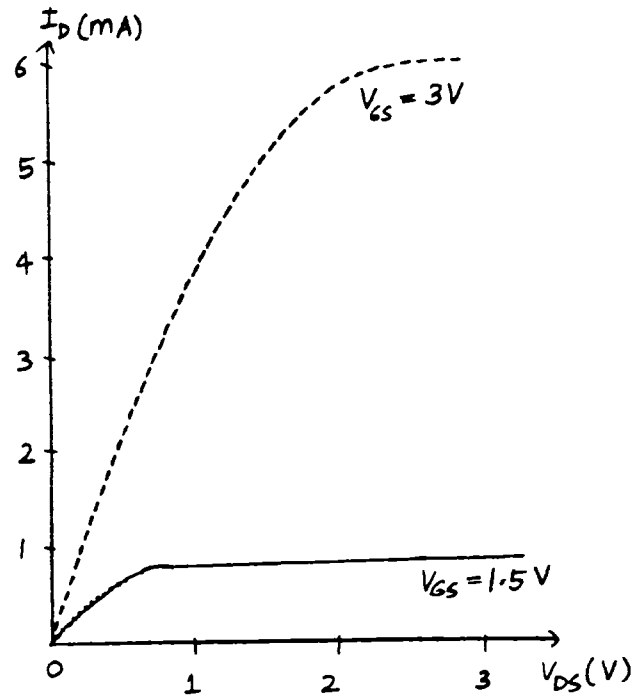
From (1.142),

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{3.9 \times 8.85 \times 10^{-14}}{80 \times 10^{-8}} \times 10^{-8} = 4.3 \frac{\text{fF}}{\mu\text{m}^2} = 4.3 \times 10^{-7} \frac{\text{F}}{\text{cm}^2}$$

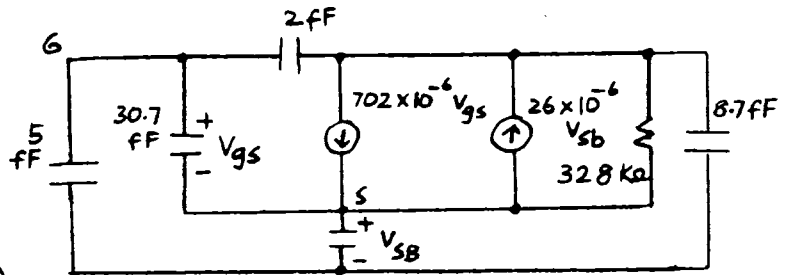
When $V_{SB} = 0$, $V_t = 0.6 \text{ V}$

When $V_{SB} = 0.5 \text{ V}$, $V_t = 0.63 \text{ V}$

When $V_{SB} = 1 \text{ V}$, $V_t = 0.65 \text{ V}$



$$\begin{aligned}
 \frac{1.16}{V_t} &= 0.6 + 0.094 (\sqrt{1.6} - \sqrt{0.6}) \\
 &= 0.646 \text{ V} \\
 I_D &= \frac{K'}{2} \frac{W}{L} (V_{GS} - V_t)^2 (1 + \lambda V_{DS}) \\
 &= \frac{194}{2} \frac{10}{1} (1 - 0.646)^2 (1 + 0.024(2)) \\
 &= 127 \mu\text{A}
 \end{aligned}$$



From (1.180),

$$\begin{aligned}
 g_m &= \sqrt{2 K' \frac{W}{L} I_D} = \sqrt{2 (194) 10 (127)} \\
 &= 702 \mu\text{A/V}
 \end{aligned}$$

From (1.199),

$$\begin{aligned}
 g_{mb} &= \gamma \sqrt{\frac{K' W/L I_D}{2(2\phi_F + V_{SB})}} = 0.094 \sqrt{\frac{194 (10) (127)}{2(0.6 + 1)}} \\
 &= 26 \mu\text{A/V}
 \end{aligned}$$

$$\begin{aligned}
 \text{From (1.194), } r_o &= \frac{1}{\lambda I_D} = \frac{1}{0.024 (127 \mu)} \\
 &= 328 \text{ k}\Omega
 \end{aligned}$$

$$\text{From (1.201), } C_{sb} = \frac{C_{sbo}}{\sqrt{1 + \frac{V_{SB}}{\phi_0}}} = \frac{20 \text{ fF}}{\sqrt{1 + \frac{1}{0.7}}} = 13 \text{ fF}$$

$$V_{DB} = V_{DS} + V_{SB} = 2 + 1 = 3 \text{ V}$$

$$\text{From (1.202), } C_{db} = \frac{C_{dbo}}{\sqrt{1 + \frac{V_{DB}}{\phi_0}}} = \frac{20 \text{ fF}}{\sqrt{1 + \frac{3}{0.7}}} = 8.7 \text{ fF}$$

$$C_{gd} = 2 \text{ fF}$$

From (1.191),

$$C_{gsi} = \frac{2}{3} W L C_{ox} = \frac{2}{3} (10) (1) (4.3 \text{ f}) = 28.7 \text{ fF}$$

$$C_{gs} = C_{gsi} + C_{gsol} = 28.7 + 2 = 30.7 \text{ fF}$$

1.17

From (1.208),

$$f_T = \frac{1}{2\pi} \frac{g_m}{C_{gs} + C_{gd} + C_{gb}} = \frac{1}{2\pi} \frac{g_m}{37.7 \times 10^{-15}}$$

From (1.179)

$$\begin{aligned}
 g_m &= K' \frac{W}{L} (V_{GS} - V_t) (1 + \lambda V_{DS}) \\
 &= 194 \frac{10}{1} (V_{GS} - 0.6) (1 + \lambda V_{DS})
 \end{aligned}$$

$$\text{Here, } 1 + \lambda V_{DS} = 1 + 0.024(3) = 1.072$$

This term is usually ignored but is included here to demonstrate its use. Ignoring the term would cause a 7.2% error

$V_{GS} \text{ (V)}$	$V_{GS} - V_t \text{ (V)}$	$g_m \left(\frac{\text{mA}}{\text{V}} \right)$	$f_T \text{ (GHz)}$
1.0	0.4	0.83	3.5
1.5	0.9	1.87	7.9
2.0	1.4	2.91	12.3

1.18

In linear region, from (1.215)

$$I_D = \frac{4nC_{ox}}{2(1 + \frac{V_{DS}}{E_L})} \frac{W}{L} [2(V_{GS} - V_t)V_{DS} - V_{DS}^2]$$

From (1.220),

$$V_{DS(Act)} = E_L \left[\sqrt{1 + \frac{2(V_{GS} - V_t)}{E_L}} - 1 \right]$$

In active region, from (1.223)

$$I_D = \frac{4nC_{ox}}{2} \frac{W}{L} V_{DS(Act)}^2$$

 $E_L = 15V$

(a)

$V_{GS}(V)$	$V_{GS} - V_t(V)$	$V_{DS(Act)}(V)$
1.0	0.40	0.395
2.0	1.40	1.34
3.0	2.40	2.23

$V_{GS} = 1V$	$V_{DS}(V)$	No vel. sat. $I_D(\mu A)$	Vel. sat. $I_D(\mu A)$
	0	0	0
	0.2	116.4	114.9
	0.4	155.2	151.2
$V_{GS} = 2V$	$V_{DS}(V)$	No vel. sat. $I_D(\mu A)$	Vel. sat. $I_D(\mu A)$
	0	0	0
	0.2	504.4	497.8
	0.4	931.2	907.0
	1.4	1901.2	1742.1
$V_{GS} = 3V$	$V_{DS}(V)$	No vel. sat. $I_D(\mu A)$	Vel. sat. $I_D(\mu A)$
	0	0	0
	0.2	892.4	880.7
	0.4	1707.2	1662.9
	1.4	4617.2	4223.0
	2.4	5587.2	4839.7

(b) $E_L = 1.5V$

$V_{GS}(V)$	$V_{GS} - V_t(V)$	$V_{DS(Act)}(V)$
1.0	0.40	0.3574
2.0	1.40	1.0397
3.0	2.40	1.5741

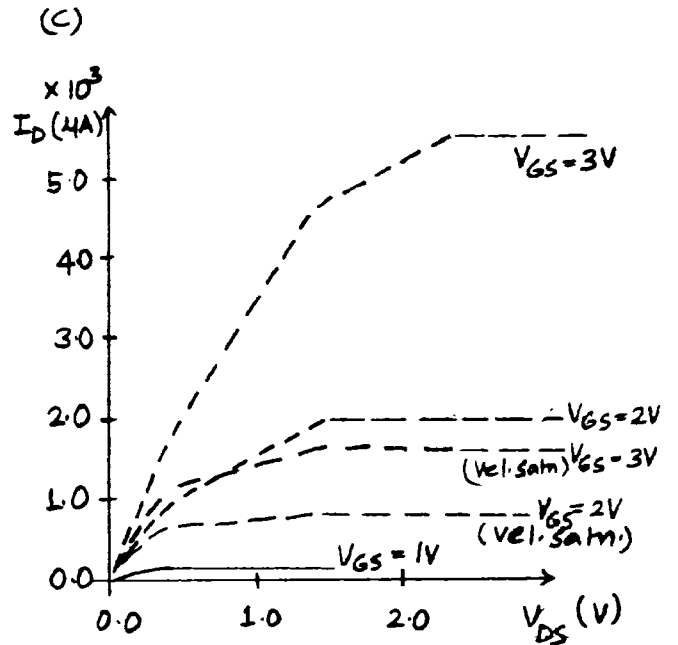
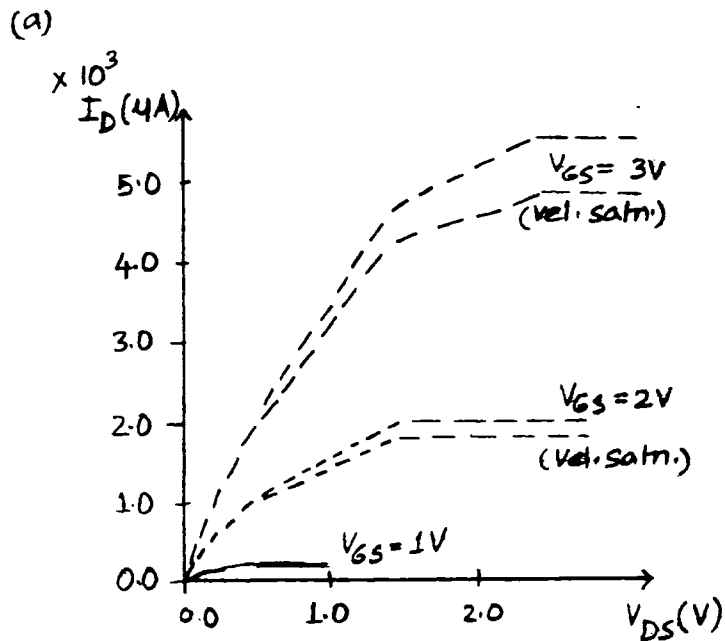
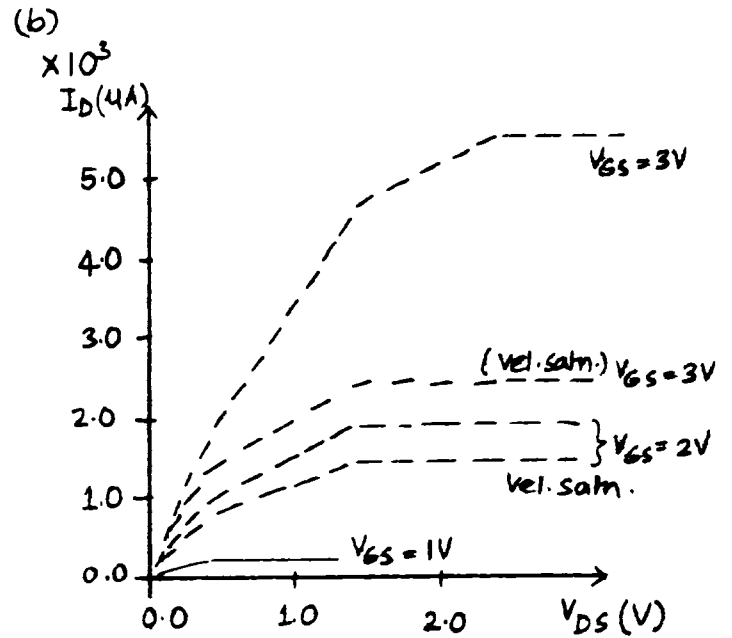
$V_{GS} = 1V$	$V_{DS}(V)$	No vel. sat. $I_D(\mu A)$	Vel. sat. $I_D(\mu A)$
	0	0	0
	0.2	116.4	102.7
	0.4	155.2	123.9
$V_{GS} = 2V$	$V_{DS}(V)$	No vel. sat. $I_D(\mu A)$	Vel. sat. $I_D(\mu A)$
	0	0	0
	0.2	504.4	445.1
	0.4	931.2	735.2
	1.4	1901.2	1048.5
$V_{GS} = 3V$	$V_{DS}(V)$	No vel. sat. $I_D(\mu A)$	Vel. sat. $I_D(\mu A)$
	0	0	0
	0.2	892.4	787.4
	0.4	1707.2	1347.8
	1.4	4617.2	2388.2
	2.4	5587.2	2403.4

(c) $E_L = 0.75V$

$V_{GS}(V)$	$V_{GS} - V_t(V)$	$V_{DS(Act)}(V)$
1.0	0.40	0.3282
2.0	1.40	0.8817
3.0	2.40	1.290

$V_{GS} = 1V$	$V_{DS}(V)$	No vel. sat. $I_D(\mu A)$	Vel. sat. $I_D(\mu A)$
	0	0	0
	0.2	116.4	91.89
	0.4	155.2	104.5

$V_{GS} = 2V$	$V_{DS} (V)$	No velocity sat. $I_D (4A)$	vel. satn. $I_D (4A)$
	0	0	0
	0.2	504.4	398.2
	0.4	931.2	607.3
	1.4	1901.2	754.1
$V_{GS} = 3V$	$V_{DS} (V)$	No velocity sat. $I_D (4A)$	vel. satn. $I_D (4A)$
	0	0	0
	0.2	892.4	704.4
	0.4	1707.2	1113.4
	1.4	4617.2	1610.7
	2.4	5587.2	1614.7



1.19

Direct calculation:

$$I_D = \frac{k'}{2} \frac{W}{L} V_{DS_{act}}^2$$

$$V_{DS_{act}} = E_c L \left[\sqrt{1 + \frac{2(V_{GS} - V_t)}{E_c L}} - 1 \right]$$

$$L = 0.5 \mu m$$

$$E_c L = 0.75$$

$$\frac{k'}{2} \frac{W}{L} = \frac{194}{2} \frac{2}{0.5} = 388 \frac{\mu A}{V^2}$$

$$V_{DS(act)} = 0.75 \left[\sqrt{1 + \frac{2(V_{GS} - 0.6)}{0.75}} - 1 \right]$$

$V_{GS}(V)$	$V_{GS} - V_t (V)$	$V_{DS_{act}} (V)$	$I_D (\mu A)$
0.6	0.0	0	0
0.8	0.2	0.179	12.43
1.0	0.4	0.328	41.7
1.2	0.6	0.459	81.7
1.6	1.0	0.686	182.59
1.8	1.2	0.787	240.31
1.9	1.3	0.835	270.52
2.0	1.4	0.882	301.83

Now use (1.230),

$$\frac{k'}{2} \frac{W}{L} = \frac{194}{2} \frac{2}{0.5} = 388 \frac{\mu A}{V^2}$$

$$R_{sx} = \frac{1}{E_c k' W} = \frac{1}{1.5 \times 10^6 (194) 2.4} = 1718.2$$

$$\frac{k' W}{L} R_{sx} = 194 \times 4 \times 1718.2 \times 10^{-6} = 1.333$$

$V_{GS}(V)$	$V_{GS} - V_t (V)$	$\frac{1}{1 + \frac{k' W}{L} R_{sx} (V_{GS} - V_t)}$	$I (\mu A)$
0.6	0.0	1.0	0
0.8	0.2	0.790	12.4
1.0	0.4	0.652	40.9
1.2	0.6	0.556	78.4
1.6	1.0	0.429	168
1.8	1.2	0.385	217

10% error occurs when $V_{GS} = 1.8V$

Reasonable since,

$$(V_{GS} - V_t)^2 = (1.2)^2 = 1.44$$

$$(I_D R_{sx})^2 = [242.8 \times 10^{-6} (1718.2)]^2 = 0.1740$$

0.17 is 12% of 1.44

1.20 simple calculation:

$$g_m = k' \frac{W}{L} (V_{GS} - V_t)$$

$$= \mu_n \frac{\epsilon_{ox}}{t_{ox}} \frac{W}{L} (V_{GS} - V_t)$$

$$= \frac{\mu_n \epsilon_{ox}}{L} (50) \frac{W}{L} (V_{GS} - V_t)$$

$$= 450 \frac{\text{cm}^2}{\text{Vs}} (3.9) (8.854 \times 10^{-14} \frac{\text{F}}{\text{cm}})$$

$$\times \frac{50(10 \mu\text{m})}{L^2} \times \frac{10^4 \mu\text{m}}{1 \text{ cm}} (0.1)$$

$$= \frac{7.769 \times 10^{-4}}{L^2} (0.1)$$

$$= \frac{1.1654 \times 10^{-3}}{L} R \frac{\text{mA}}{\text{V}^2}$$

L (μm)	R	$g_m = \frac{1.1654 \times 10^{-3}}{L} R \frac{\text{mA}}{\text{V}}$
10	6.6×10^{-3}	0.77
2	3.175×10^{-2}	18.5
1	6.066×10^{-2}	70.7
0.5	0.11148	260
0.4	0.134	390

L (μm)	$g_m (\text{mA/V}^2)$
0.4	485 (24% error)
0.5	310 (20% error)
1.0	77.7 (10% error)
2.0	19.4
10.0	0.77

Now with velocity saturation,

$$g_m = W C_{ox} \mu_n E_c R \text{ where,}$$

$$R = \frac{\sqrt{1 + \frac{2(V_{GS} - V_t)}{E_c L}} - 1}{\sqrt{1 + \frac{2(V_{GS} - V_t)}{E_c L}}}$$

$$g_m = (10 \mu\text{m}) (3.9) \left(\frac{8.854 \times 10^{-14} \text{F}}{\text{cm}} \right) \frac{450 \text{ cm}^2}{\text{V sec}} \frac{L}{50} \times 1.5 R \times \frac{10^4 \mu\text{m}}{1 \text{ cm}}$$

$$= \frac{7.77 \times 10^{-5}}{L} R (E_c W) \frac{\text{mA}}{\text{V}^2}$$

1.21

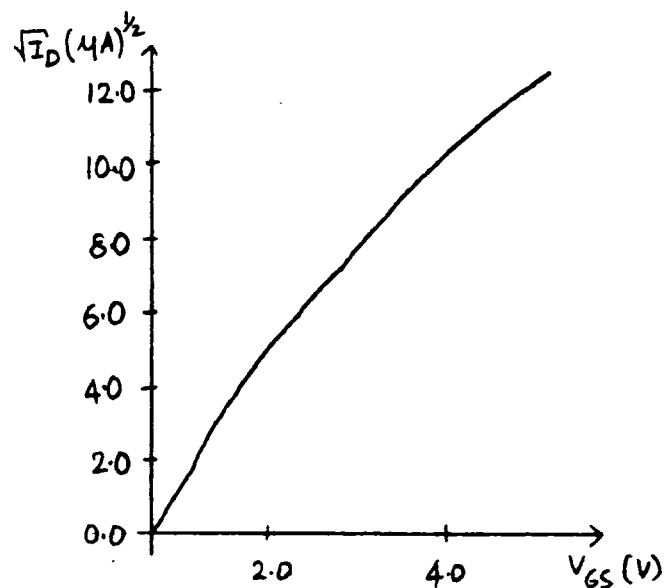
From (1.223), $I_D = \frac{\mu_n C_{ox}}{2} \frac{W}{L} [V_{DS(akt)}]^2$

From (1.220), $V_{DS(akt)} = E_c L \left[\sqrt{1 + \frac{2(V_{GS} - V_t)}{E_c L}} - 1 \right]$

$E_c L = 1.5 \quad V_t = 0.7 \text{ V}$

$V_{GS} \text{ (V)}$	$V_{DS(akt)} \text{ (V)}$	$I_D \text{ (}\mu\text{A)}$	$\sqrt{I_D} \text{ (}\mu\text{A)}^{1/2}$	$\frac{\mu_n' W}{2L} (V_{GS} - V_t)^2 \text{ (}\mu\text{A)}$	$\sqrt{\frac{\mu_n' W}{2L} (V_{GS} - V_t)^2} \text{ (}\mu\text{A)}^{1/2}$	$V_{GS} - V_t \text{ (V)}$
0.7	0.0	0.0	0.0	0.0	0.0	0.0
0.8	0.097	0.253	0.503	0.27	0.520	0.1
0.9	0.188	0.956	0.978	1.08	1.04	0.2
1.0	0.275	2.04	1.43	2.43	1.56	0.3
1.5	0.656	11.6	3.41	17.3	4.16	0.8
2.0	0.980	25.9	5.09	45.6	6.75	1.3
3.0	1.52	62.4	7.89	143	12.0	2.3
4.0	1.99	106.9	10.3	294	17.1	3.3
5.0	2.39	154.2	12.4	499	22.3	4.3

For large V_{GS} , current is limited by velocity saturation.



1.22

$$I_D = K_x \frac{W}{L} e^{V_{GS}/nV_T} (1 - e^{-V_{DS}/V_T})$$

$$g_m = \frac{\partial I_D}{\partial V_{GS}} = \frac{1}{nV_T} K_x \frac{W}{L} e^{V_{GS}/nV_T} (1 - e^{-V_{DS}/V_T})$$

$$= \frac{1}{nV_T} I_D = \frac{10 \times 10^{-9}}{1.5 \times 26 \times 10^{-3}} = 2.56 \times 10^{-7}$$

$$= 0.256 \mu A/V$$

$$f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd} + C_{gb})} = \frac{0.256 \mu A/V}{2\pi(10 \text{ fF})}$$

$$= 4.076 \text{ MHz}$$

CHAPTER 2

2.1

From Fig. (2.2)

For p-type Si,

$$N_A = 1.5 \times 10^{16} \text{ atoms/cm}^3$$

For n-type Si,

$$N_D = 6 \times 10^{15} \text{ atoms/cm}^3$$

2.2

$$R_D = \frac{\ell}{T} = \frac{1 \Omega\text{-cm}}{5.4 \mu\text{m}} = \frac{1 \Omega\text{-cm}}{5 \times 10^{-4} \text{cm}} \\ = 2000 \Omega/\square$$

2.3

The doping profile has the form

$$N_D(x) = N_{D0} \exp\left(-\frac{x}{L}\right)$$

The first step is to determine

N_{D0} and L . Since at $x=0$,

$$N_D(x) = 10^{17} \text{ cm}^{-3}, \text{ then}$$

$$N_{D0} = 10^{17} \text{ cm}^{-3}$$

$$\text{At } x = 0.5 \mu\text{m}, N_D(x) = \frac{1}{e} N_D(0)$$

$$\therefore N_{D0} e^{-1} = N_{D0} \exp\left(-\frac{0.5 \mu\text{m}}{L}\right)$$

$$\therefore L = 0.5 \mu\text{m}$$

Thus,

$$N_D(x) = 10^{17} \exp\left(-\frac{x}{0.5 \mu\text{m}}\right)$$

The junction will exist at the point where the net doping

$$N_D(x) - N_A(x) = 0$$

$$\therefore 10^{17} \exp\left(-\frac{x_j}{0.5 \mu\text{m}}\right) = 10^{15}$$

$$\therefore x_j = 0.5 \mu\text{m} \ln \frac{10^{17}}{10^{15}} = 2.3 \mu\text{m}$$

The sheet resistance is given by :

$$R_D = \left[q \bar{\mu}_n \int_0^{x_j} [N_D(x) - N_A(x)] dx \right]^{-1}$$

Since the effective doping

is $N_D(x) - N_A(x)$

$$\therefore q \left[\frac{800 \text{ cm}^2}{\text{V-sec}} \right] \int_0^{2.3 \mu\text{m}} \left[10^{17} e^{-\frac{x}{0.5 \mu\text{m}}} - 10^{15} \right] dx \\ = q \left[\frac{800 \text{ cm}^2}{\text{V-sec}} \right] \left\{ \left[-0.5 \times 10^{11} - 2.3 \times 10^{11} \right] + 0.5 \times 10^{13} \right\} \\ = 1.6 \times 10^{-19} \times 800 \times 4.72 \times 10^{12} \\ = 1.6 \times 8 \times 4.72 \times 10^{-5} \\ \therefore R_D = \left[6.04 \times 10^{-4} \right]^{-1} = 1655 \Omega/\square$$

2.4

$$\text{For the resistor } \frac{L}{W} = \frac{200 \mu\text{m}}{5 \mu\text{m}} = 40$$

Base-diffused

$$R = 40 \times 100 \Omega/\square = 4 \text{ k}\Omega$$

Emitter-diffused

$$R = 40 \times 5 \Omega/\square = 200 \Omega$$

Pinch

$$R = 40 \times 5 \text{ k}\Omega/\square = 200 \text{ k}\Omega$$

2.5

From (2.17), for an npn-transistor,

$$Q_B = \frac{A \bar{D}_n q n_i^2}{I_c} \exp\left(\frac{V_{BE}}{V_T}\right)$$

For $V_{BE} = 520 \text{ mV}$,

$$Q_B = \frac{(10^{-4} \text{ cm}^2) (13 \frac{\text{cm}^2}{\text{sec}}) (1.6 \times 10^{-19}) (2 \times 10^{20})}{10^{-5}} e^{(520/26)} \\ = 2.02 \times 10^{12} \text{ atoms/cm}^2$$

For $V_{BE} = 580 \text{ mV}$, same expression gives : $Q_B = 2 \times 10^{13} \text{ atoms/cm}^2$

For $Q_B = 2.02 \times 10^{12}$

$$R_D = [q \mu_p Q_B]^{-1}$$

$$= \left[(1.6 \times 10^{-19}) (150 \frac{\text{cm}^2}{\text{V}\cdot\text{sec}}) (2.02 \times 10^{12}) \right]^{-1}$$

$$= (485 \times 10^{-17})^{-1} = 21 \text{ K}\Omega/\square$$

2.6

(a) Series base R:

Emitter periphery adjacent to a base contact is:

$$p = 4 \times 40 \mu\text{m} = 160 \mu\text{m}$$

Distance from base contact to emitter is: $10 \mu\text{m}$

$$\therefore R_B = R_D \left(\frac{10}{160} \right) = 100 \frac{\Omega}{\square} \left(\frac{1}{16} \right)$$

$$= 6.2 \Omega$$

(b) Series collector resistance:

For each of two emitters the effective buried layer dimensions are:

$$W_{BL} = (W + 2T) = 20 \mu\text{m} + 2(10 \mu\text{m})$$

$$= 40 \mu\text{m}$$

$$L_{BL} = (L + 2T) = 40 \mu\text{m} + 2(10 \mu\text{m})$$

$$= 60 \mu\text{m}$$

Using (2.18),

$$a = \left(\frac{20}{40} \right)^{-1}, \quad b = \left(\frac{40}{60} \right)^{-1}$$

$$2\gamma_{c1} = \frac{(5 \Omega\text{-cm})(10 \mu\text{m})}{(20 \mu\text{m})(40 \mu\text{m})} \ln \frac{2/1.5}{0.5}$$

$$= 360 \Omega$$

$$\therefore \gamma_{c1} = 180 \Omega$$

$$\gamma_{c2} = R_{BL} \left(\frac{L}{W} \right) = 20 \frac{\Omega}{\square} \left(\frac{40}{140} \right) = 5.7 \Omega$$

γ_{c3} : for buried layer

$$L_{eff} = 140 \mu\text{m}$$

$$W_{eff} = 14 \mu\text{m} + 2T = 34 \mu\text{m}$$

For top N^+ : $L = 140 \mu\text{m}$
 $W = 14 \mu\text{m}$

$$\therefore a = \frac{34}{14} = 2.43; \quad b = 1$$

$$\therefore \gamma_{c3} = \frac{(5 \Omega\text{-cm})(10 \mu\text{m})}{(140 \mu\text{m})(14 \mu\text{m})} \ln \frac{2.43}{2.43-1}$$

$$= 158 \Omega$$

$$\therefore R_c = 158 + 180 + 5.7 = 344 \Omega$$

(c) $C_{jc} = (A_{bottom} + A_{sidewall}) C_{jc}/\text{area}$

$$= \left[(140 \mu\text{m})(60 \mu\text{m}) + \frac{\pi \cdot 3 \mu\text{m}(280 \mu\text{m} + 120 \mu\text{m})}{2} \right] \times 10^{-4} \frac{\text{pF}}{(\mu\text{m})^2}$$

$$= (8400 + 1885) \times 10^{-4}$$

$$= 1.03 \text{ pF}$$

(d) $C_{je} = (C_{jebottom} + C_{jesidewall})$

$$= 2 [A_{bottom} + A_{sidewall}] C_{je}/\text{area}$$

$$= 2 \left[(20 \mu\text{m})(40 \mu\text{m}) + \frac{\pi \cdot 2 \mu\text{m}(40 \mu\text{m} + 80 \mu\text{m})}{2} \right] \times 10^{-4} \frac{\text{pF}}{(\mu\text{m})^2}$$

$$= 2.4 \text{ pF}$$

(e) $C_{\text{substrate}} = C_{\text{sidewall}} + C_{\text{epi-sub}} + C_{\text{BL-sub}}$

$$C_{\text{sidewall}} = \frac{\pi}{2} \times (17 \mu\text{m}) \left[175 \mu\text{m} \times 2 + 140 \mu\text{m} \times 2 \right] \times 10^{-4} \frac{\text{pF}}{(\mu\text{m})^2}$$

$$= 1.6 \text{ pF}$$

$$C_{\text{epi-sub}} = (175 \times 140 - 85 \times 126) \times 10^{-4} \frac{\text{pF}}{(\mu\text{m})^2}$$

$$= 1.4 \text{ pF}$$

$$C_{\text{BL-sub}} = (85 \times 126) \times 3.3 \times 10^{-4} = 3.5 \text{ pF}$$

$$\therefore C_{\text{substrate}} = 6.5 \text{ pF}$$

$$(f) I_S = \frac{q n_i^2}{Q_B / \bar{D}_n} A_{EB}$$

From text example,

$$\begin{aligned} \frac{Q_B}{\bar{D}_n} &= 5.7 \times 10^{11} \text{ cm}^{-4} \text{ sec} \\ \therefore I_S &= \frac{1.6 \times 10^{-19} \times 2 \times 10^{20} \times 1600 \text{ } \mu\text{m}^2 \times (10^{-8} \frac{\text{cm}^2}{\mu\text{m}^2})}{5.7 \times 10^{11}} \\ &= 0.9 \times 10^{-15} \text{ A} \end{aligned}$$

2.7

From (2.24), the p falloff begins

$$\text{at } I_C = q A N_D \frac{D_p}{W_B}$$

For this structure, the area A is the product of the emitter diffusion periphery $120 \mu\text{m}$, and the effective sidewall depth.

Regarding the sidewall as a quarter-cylinder this effective depth is the emitter junction depth multiplied by $\pi/2$. Thus,

$$A_{\text{eff}} = (120 \mu\text{m})(3 \mu\text{m})(\pi/2) = 5.65 \times 10^{-6} \text{ cm}^2$$

From Fig.(2.2), the donor density corresponding to a resistivity of $0.5 \Omega\text{-cm}$ is $1.2 \times 10^{16} \text{ cm}^{-3}$. Thus,

$$\begin{aligned} I_C &= \frac{(1.6 \times 10^{-19})(5.65 \times 10^{-6})(1.2 \times 10^{16})(10)}{8 \times 10^{-4}} \\ &= 13.56 \times 10^{-5} = 136 \text{ } \mu\text{A} \end{aligned}$$

2.8

From (2.17), for a pnp transistor

$$Q_B = q A \bar{D}_p \frac{n_i^2}{I_C} \exp\left(\frac{V_{BE}}{V_T}\right)$$

For this device,

$$\begin{aligned} A &= 2 \times (30 \mu\text{m} \times 75 \mu\text{m}) + 2 \times (10 \mu\text{m} \times 30 \mu\text{m}) \\ &= 5100 (\mu\text{m})^2 \end{aligned}$$

For $V_{BE} = 525 \text{ mV}$

$$\begin{aligned} Q_B &= \frac{1.6 \times 10^{-19} \times 5100 \times 10^{-8} \times 10 \times 2 \times 10^{20}}{10^{-5}} \exp\left(\frac{525}{26}\right) \\ &= 9.6 \times 10^{11} \end{aligned}$$

Using Fig.(2.2), the donor density corresponding to $2 \Omega\text{-cm}$ is

$$2.5 \times 10^{15} \text{ cm}^{-3}$$

since, $Q_B = W_B N_D$, then

$$\begin{aligned} W_B &= \frac{Q_B}{N_D} = \frac{9.6 \times 10^{11}}{2.5 \times 10^{15}} = 3.84 \times 10^{-4} \text{ cm} \\ &= 3.84 \text{ } \mu\text{m} \end{aligned}$$

Since the p -diffusion depth is $3 \mu\text{m}$, the total epi thickness is $6.84 \mu\text{m}$, for $V_{BE} = 525 \text{ mV}$. By a similar calculation, the total depth for $V_{BE} = 560 \text{ mV}$ is $17.45 \mu\text{m}$

The same resistances are:

For $V_{BE} = 525 \text{ mV}$

$$\begin{aligned} R_D &= [q \bar{\mu}_n Q_B]^{-1} \\ &= [(1.6 \times 10^{-19})(800)(9.6 \times 10^{11})]^{-1} \\ &= [12 \times 10^{-5}]^{-1} = 8 \text{ k}\Omega/\square \end{aligned}$$

For $V_{BE} = 560 \text{ mV}$

$$R_D = 2.12 \text{ k}\Omega/\square$$

2.9

First consider the $6 \mu\text{m}$ resistor,

For $10 \text{ k}\Omega$ we need 100 squares or $600 \mu\text{m}$ of length. The total

resistor area is that of the body plus clubheads, or

$$A_{\text{bottom}} = 600 \mu\text{m} \times 6 \mu\text{m} + 2 (26 \mu\text{m})^2 \\ = 4952 (\mu\text{m})^2$$

The sidewall area is equal to the total periphery multiplied by $(3 \mu\text{m}) (\pi/2)$.

The periphery is,

$$P = 600 \mu\text{m} + 600 \mu\text{m} + 6 \times 26 \mu\text{m} + 2 (26 - 6) \mu\text{m} \\ = 1396 \mu\text{m}$$

Thus,

$$A_{\text{sidewall}} = 1396 \mu\text{m} \times 3 \mu\text{m} \times \frac{\pi}{2} \\ = 6578 (\mu\text{m})^2$$

The total area is,

$$A_{\text{total}} = 11,530 (\mu\text{m})^2$$

For the 10^{15} cm^{-3} epi concentration the capacitance per unit area for zero bias is from Fig. (2.29) equal to $10^{-4} \text{ pF}/(\mu\text{m})^2$

$$\text{Thus, } C_{\text{total}} = 11,530 (\mu\text{m})^2 \times 10^{-4} \frac{\text{pF}}{(\mu\text{m})^2} \\ = 1.15 \text{ pF}$$

For the $12 \mu\text{m}$ resistor, we need $1200 \mu\text{m}$ of length

$$\text{Thus, } A_{\text{bottom}} = 12 \mu\text{m} \times 1200 \mu\text{m} + 2 (26 \mu\text{m})^2 \\ = 15,750 (\mu\text{m})^2$$

$$A_{\text{sidewall}} = \frac{\pi}{2} [1200 \times 2 + 26 \times 6 + 2 (26 - 12)] \times 3 \\ = 12,177 (\mu\text{m})^2$$

$$\therefore A_{\text{total}} = 27,929 (\mu\text{m})^2$$

$$\therefore C_{\text{total}} = 27,929 (\mu\text{m})^2 \times 10^{-4} \frac{\text{pF}}{(\mu\text{m})^2} = 2.8 \text{ pF}$$

2.10

$$(1) I_s = A_{EB} q \frac{n_i^2}{Q_B} \bar{D}_p \\ = [90 \mu\text{m} \times 75 \mu\text{m} - 30 \mu\text{m} \times 55 \mu\text{m}] \\ \times 10^{-8} \frac{\text{cm}^2}{\mu^2} \times (1.6 \times 10^{-19}) (2 \times 10^{20}) (10 \text{ cm}^2/\text{sec}) \\ \frac{(10^{15} \text{ atoms}/\text{cm}^3) \times 14 \mu\text{m} \times 10^{-4} \text{ cm}}{\mu\text{m}} \\ = 1.17 \times 10^{-14} \text{ A}$$

$$(2) C_{je} = A_{\text{bottom}} \times 10^{-4} \text{ pF}/(\mu\text{m})^2 \\ + A_{\text{sidewall}} \times 10^{-3} \text{ pF}/(\mu\text{m})^2 \\ = (90 \times 75 - 30 \times 55) (\mu\text{m})^2 \times 10^{-4} \frac{\text{pF}}{(\mu\text{m})^2} \\ + \frac{\pi}{2} (60 + 110) (3) (\mu\text{m})^2 \times 10^{-3} \frac{\text{pF}}{(\mu\text{m})^2} \\ = 0.51 + 0.8 = 1.31 \text{ pF}$$

$$(3) C_M = C_{\text{epi-sidewall}} + C_{\text{bottom}} \\ = \frac{\pi}{2} (40 \times 2 + 125 \times 2) \times (17) (\mu\text{m})^2 \times 10^{-4} \frac{\text{pF}}{(\mu\text{m})^2} \\ + (40 \times 125) (\mu\text{m})^2 \times 10^{-4} \frac{\text{pF}}{(\mu\text{m})^2} \\ = 1.4 + 1.75 = 3.15 \text{ pF}$$

$$(4) \tau_F = \frac{W_B^2}{2 D_p} = \frac{[(14 \mu\text{m}) (10^{-4} \text{ cm}/\mu\text{m})]^2}{2 \times 10 \text{ cm}^2/\text{sec}} \\ = 98 \text{ nsec}$$

2.11

For an npn transistor

$$Q_B = \frac{q A \bar{D}_n n_i^2}{I_C} \exp\left(\frac{V_{BE}}{V_T}\right) \\ = \frac{(1.6 \times 10^{-19}) (10^{-4} \text{ cm}^2) (13) (2 \times 10^{20}) e^{\frac{480}{26}}}{10^{-5}} \\ = 4.3 \times 10^{11} \text{ atoms/cm}^2$$

$$R_{\square} = [q \mu_p Q_B]^{-1} \\ = [1.6 \times 10^{-19} \times 150 \frac{\text{cm}^2}{\text{V-sec}} \times 4.3 \times 10^{11}]^{-1} \\ = 97 \text{ k}\Omega/\square$$

In order to contain $4.3 \times 10^{11} \frac{\text{atoms}}{\text{cm}^2}$ of the n-type epi-impurity, the width of the collector depletion layer at punch-thru is, $W_D = \frac{4.3 \times 10^{11} \text{ atoms/cm}^2}{10^{15} \text{ cm}^{-3}}$
 $= 4.3 \times 10^{-4} \text{ cm} = 4.3 \mu\text{m}$

Using (1.15) and assuming that $N_A \gg N_D$,

$$W_D = \sqrt{\frac{2E(\psi_0 + \psi_R)}{q N_D}} = 4.3 \mu\text{m}$$

$$= \sqrt{\frac{2 \times 1.04 \times 10^{-12} \times (0.55 + V_R)}{1.6 \times 10^{-19} \times 10^{15}}}$$

$$\therefore V_R = 13.7 \text{ V}$$

For $V_{BE} = 560 \text{ mV}$, same expressions

give, $Q_B = 9.4 \times 10^{12} \text{ atoms/cm}^2$

$$R_D = 4.43 \text{ k}\Omega/\square$$

$$W_D = 94 \mu\text{m}$$

$$V_R = 6,796 \text{ V}$$

2.12

From (1.157),

$$I_D = \frac{\mu_n C_{ox}}{2} \frac{W}{L} (V_{GS} - V_t)^2$$

$$100 \mu\text{A} = \frac{\mu_n C_{ox}}{2} \frac{W}{L} (1.5 - V_t)^2 \rightarrow (1)$$

$$10 \mu\text{A} = \frac{\mu_n C_{ox}}{2} \frac{W}{L} (0.8 - V_t)^2 \rightarrow (2)$$

Divide (1) by (2) and solve for $V_t \rightarrow$ gives $V_t = 0.48 \text{ V}$.

Substituting for V_t in (1) gives,

$$\mu_n C_{ox} \frac{W}{L} = 191 \mu\text{A/V}$$

$$2.13 \quad V_t = \phi_{Ms} + 2\phi_f + \frac{Q_b}{C_{ox}} - \frac{Q_{ss}}{C_{ox}}, \quad (2.27)$$

(i) For unimplanted transistors,

From Table 2.1, $\phi_{Ms} = -0.1 \text{ V}$

From (2.28),

$$\phi_f = \frac{KT}{q} \ln \frac{N_A}{n_i} = 0.026 \ln \frac{10^{16}}{1.45 \times 10^{10}}$$

$$= 0.35$$

From (2.30),

$$C_{ox} = 0.86 \text{ fF}/(\mu\text{m})^2$$

$$\frac{Q_{ss}}{C_{ox}} = \frac{1.6 \times 10^{-19} \times 10^{11}}{8.6 \times 10^{-8}} = 0.19 \text{ V}$$

From (1.137),

$$Q_{b0} = \sqrt{2q N_A E \cdot 2\phi_f}$$

$$= [2 \times 1.6 \times 10^{-19} \times 10^{16} \times 11.6 \times 8.86 \times 10^{-14} \times 2 \times 0.35]^{1/2} = 4.8 \times 10^{-8} \frac{\text{Coulombs}}{\text{cm}^2}$$

$$\therefore V_t = -0.1 - 2 \times 0.35 - \frac{4.8 \times 10^{-8}}{8.6 \times 10^{-8}} - 0.19$$

$$= -1.55$$

(ii) For implanted transistors,

$$N_A = 1 \times 10^{16} - 0.9 \times 10^{16} = 10^{15} \text{ cm}^{-3}$$

From Fig. (2.29), the depletion layer width corresponding to a doping level of 10^{15} cm^{-3} is $\sim 1 \mu\text{m}$, while the implant depth is only $0.3 \mu\text{m}$

$$\therefore V_t(\text{implant}) = -1.55$$

$$+ \frac{0.9 \times 10^{16} \times 0.3 \times 10^{-4} \times 1.6 \times 10^{-19}}{8.6 \times 10^{-8}}$$

$$= -1.05$$

2.14

The metallurgical channel length is

$$L = L_{\text{drawn}} - 2L_d = 7 \mu\text{m} - 2(0.3) = 6.4 \mu\text{m}$$

The effective channel length is L minus the width of the depletion region at the drain. In the active region, the voltage at the drain end of the channel is $= V_{GS} - V_t = V_{OV}$

To calculate V_{OV} , assume at first that $L_{\text{eff}} = L$. Then from (1.166)

$$V_{OV} = \sqrt{\frac{2I_D}{k' \frac{W}{L}}} = \sqrt{\frac{2(10 \mu\text{A})}{700 \frac{\text{cm}^2}{\text{V}\cdot\text{s}} \cdot 0.86 \frac{\text{FF}}{\mu^2} \left(\frac{100}{6.4}\right)}} = 0.15 \text{ V}$$

Thus, the voltage across the drain depletion region $= 5 - 0.15 = 4.85 \text{ V}$

To estimate the depletion-region width, assume it is a one-sided step junction that mainly exists in the lightly doped side. Since the channel and the drain are both n-type regions, the built-in potential of the junction is near zero. Using (1.14) and assuming $N_D \gg N_A$,

$$X_d = \sqrt{\frac{2\epsilon(V_{DS} - V_{OV})}{qN_A}} = \sqrt{\frac{2(1.04 \times 10^{-12})(5 - 0.15)}{1.6 \times 10^{-19}(2 \times 10^{16} + 10^5)}} = 0.55 \mu\text{m}$$

$$\text{So, } L_{\text{eff}} = 7 \mu\text{m} - 2(0.3 \mu\text{m}) - 0.55 \mu\text{m} = 5.85 \mu\text{m}$$

$$\text{Therefore, since } r_o = \frac{1}{\lambda I_D} = \frac{L_{\text{eff}}}{I_D} \frac{dX_d}{dV_{DS}} \Rightarrow r_o = 5 \text{ M}\Omega = \frac{5.85 \mu\text{m}}{10 \mu\text{A}} \frac{dX_d}{dV_{DS}}$$

So, $\frac{dX_d}{dV_{DS}} = 0.12 \frac{\mu\text{m}}{\text{V}}$. Since, the other device uses the same technology, $\frac{dX_d}{dV_{DS}}$ is unchanged. But, should calculate V_{OV} for 2nd transistor,

$$V_{OV} = \sqrt{\frac{2I}{k' \frac{W}{L}}} = \sqrt{\frac{2(30)}{(60.2) \frac{50}{12 - 2(0.3)}}} = 0.48 \text{ V}$$

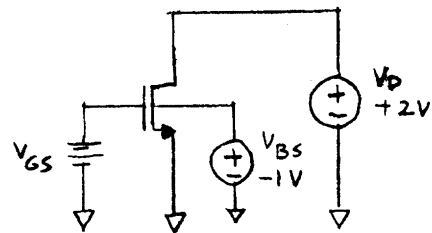
$$\text{So, } X_d = \sqrt{\frac{2(1.04 \times 10^{-12})(5 - 0.48)}{1.6 \times 10^{-19}(2.1 \times 10^{16})}} = 0.53 \mu\text{m}$$

$$L_{\text{eff}_2} = 12 - 2(0.3) - 0.53 = 10.87 \mu\text{m}$$

$$r_o = \frac{L_{\text{eff}}}{I_D} \frac{dX_d}{dV_{DS}} = \frac{10.87 \mu\text{m}}{30 \mu\text{A}} \frac{1}{0.12} = 3.02 \text{ M}\Omega$$

Note that using the same V_{OV} as for the 1st transistor (0.15V) gives an answer of 3.1 M Ω . (The change hardly matters)

2.15



First to estimate X_d and L_{eff}

$$L_{\text{eff}} = L_{\text{drawn}} - 2L_d - X_d \rightarrow (1)$$

$$X_d = \sqrt{\frac{2\epsilon_{\text{Si}}(V_{DS} - V_{OV})}{q(N_A + N_i)}} \rightarrow (2)$$

$$I_D = \frac{\mu_n C_{\text{ox}}}{2} \frac{W}{L_{\text{eff}}} (V_{GS} - V_t)^2 \rightarrow (3)$$

L_{eff} , X_d and $V_{OV} = (V_{GS} - V_t)$ can be

found by solving (1), (2), (3).

To avoid solving non-linear equations, the following procedure is used: find x_d by substituting $L_{\text{drawn}} - 2L_d$ for L_{eff} in (3) and use the result in (2).

From (3),

$$V_{GS} - V_t = \sqrt{\frac{2I_D}{\mu_n C_{ox} W/L_{\text{eff}}}}$$

$$= \sqrt{\frac{2 \times 20 \mu A}{450 \frac{\text{cm}^2}{\text{V} \cdot \text{sec}} \cdot 4.32 \frac{\text{fF}}{(\mu\text{m})^2} \left(\frac{10 \mu\text{m}}{1 \mu\text{m} - 2(0.09 \mu\text{m})} \right)}}$$

$$= 0.130 \text{ V}$$

From (2),

$$x_d = \sqrt{\frac{2 \times 11.6 \times 8.86 \times 10^{-14} (2 - 0.13)}{1.6 \times 10^{-19} (5 \times 10^{16} + 4 \times 10^{16})}}$$

$$= 0.231 \mu\text{m}$$

From (1),

$$L_{\text{eff}} = 1 \mu\text{m} - 2(0.09 \mu\text{m}) - 0.231 \mu\text{m}$$

$$= 0.589 \mu\text{m}$$

$$(a) \quad g_m = \sqrt{\frac{2K' W}{L_{\text{eff}}} I_D}$$

$$= \sqrt{\frac{2 \times 194 \frac{\mu A}{V^2} \times \frac{10}{0.589} \times 20 \mu A}{}}$$

$$= 363 \mu A/V$$

$$(b) \quad \text{From (1.200), } g_{mb} = \frac{\gamma g_m}{2\sqrt{2\phi_f + V_{SB}}} = \chi g_m$$

$$\text{where } \gamma = \frac{\sqrt{2qE_{si} N_T}}{C_{ox}} \quad \text{from (1.141)} \quad \text{and}$$

N_T is the effective dopant density at the bottom of the channel-substrate depletion layer, it can be

either N_A (substrate doping) or $N_A + N_i$. To determine which one applies, we have to find $x'_{d\text{max}}$, i.e., the depletion depth under the channel,

$$x'_{d\text{max}} = \sqrt{\frac{2E_{si}(2|\phi_f| + V_{SB})}{q(N_A + N_i)}}$$

But,

$$\phi_f = \frac{KT}{q} \ln \frac{N_A + N_i}{n_i}$$

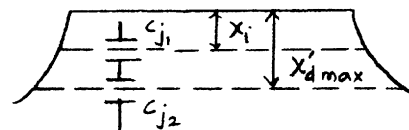
$$= 0.026 \ln \frac{4 \times 10^{16} + 5 \times 10^{15}}{1.45 \times 10^{10}} = 0.389$$

$$\therefore x'_{d\text{max}} = \sqrt{\frac{2 \times 11.6 \times 8.86 \times 10^{-14} (2 \times 0.389 + 1)}{1.6 \times 10^{-19} (4 \times 10^{16} + 5 \times 10^{15})}}$$

$$= 0.225 \mu\text{m}$$

$> 0.16 \mu\text{m}$ (effective implant depth)

Since $x'_{d\text{max}} > x_i$, the depletion capacitor is the series combination of the capacitors as shown,



Now χ can be calculated from the following relationships,

$$\chi = \frac{C_{js}}{C_{ox}}, \quad C_{js} = \frac{C_{j1} C_{j2}}{C_{j1} + C_{j2}}$$

$$C_{j1} = \frac{E_{si}}{x_i}, \quad C_{j2} = \frac{E_{si}}{x'_{d\text{max}} - x_i}$$

The actual depletion depth is

$$x_{d\max} = \left[\frac{2 \epsilon_{si}}{q N_A} (\phi_f + |\phi_p| + V_{SB} - x_i^2 \frac{N_i}{N_A}) \right]^{1/2}$$

(cf. Muller and Kamins : Device Electronics for Integrated Circuits, 2nd ed., 1986; equation (10.6.2))

$$\phi_f = \frac{KT}{q} \ln \frac{N_A}{N_i} = 0.026 \ln \frac{5 \times 10^5}{1.45 \times 10^{10}} = 0.33 \text{ V}$$

$$x_{d\max} = \left[\frac{2 \times 11.6 \times 8.86 \times 10^{-14} (0.33 + 0.389 + 1)}{1.6 \times 10^{-19} \times 5 \times 10^{15}} - \frac{(0.16 \times 10^{-4} \text{ cm})^2 (4 \times 10^{16})}{5 \times 10^{15}} \right]^{1/2}$$

$$= 0.453 \text{ } \mu\text{m}$$

$$C_{j1} = \frac{11.6 \times 8.86 \times 10^{-14}}{0.16 \times 10^{-4}} = 6.42 \times 10^{-8} \text{ F/cm}^2$$

$$C_{j2} = \frac{11.6 \times 8.86 \times 10^{-14}}{(0.453 - 0.16) \times 10^{-4}} = 3.51 \times 10^{-8} \text{ F/cm}^2$$

$$C_{js} = 2.27 \times 10^{-8} \text{ F/cm}^2$$

$$\therefore \chi = \frac{2.27 \times 10^{-8}}{4.32 \times 10^{-7}} = 0.0526$$

$$g_{mb} = \chi g_m = 0.0526 \times 363 \times 10^{-6} = 19.1 \frac{\mu\text{A}}{\text{V}}$$

(c) From (2.37),

$$V_{ov} = \sqrt{\frac{2 I_D}{\chi' (W/L_{eff})}} = \sqrt{\frac{2 \times 20 \mu\text{A}}{194 \mu\text{A/V}^2 (10 \mu\text{m}/0.589 \mu\text{m})}}$$

$$= 0.110 \text{ V}$$

$$x_d = \sqrt{\frac{2 \epsilon_{si} (V_{DS} - V_{ov})}{q (N_A + N_i)}}$$

$$\frac{dx_d}{dV_{DS}} = \frac{x_d}{2(V_{DS} - V_{ov})} = \frac{0.231 \mu\text{m}}{2(2 - 0.11)} = 0.061 \mu\text{m/V}$$

$$\therefore Y_o = \left(\frac{I_D}{L_{eff}} \frac{dx_d}{dV_{DS}} \right)^{-1} = \left(\frac{20 \mu\text{A}}{0.589 \mu\text{m}} \times 0.061 \mu\text{m/V} \right)^{-1}$$

$$= 482.78 \text{ k}\Omega$$

$$(d) C_{gs} = \frac{2}{3} W L_{eff} C_{ox} + C_{OL}$$

$$= \frac{2}{3} \times 10 \times 0.589 \times 4.32 \times 10^{-15} + 0.35 \times 10^{-15} \times 10$$

$$= 20.5 \text{ fF}$$

$$(e) C_{gd} = C_{OL} = 0.35 \times 10^{-15} \times 10 = 3.5 \text{ fF}$$

$$(f) C_{db} = \frac{C_{j0} \times (\text{drain area}) + C_{jsw0} \times \text{periphery}}{\sqrt{1 + V_{DB}/\phi_0}}$$

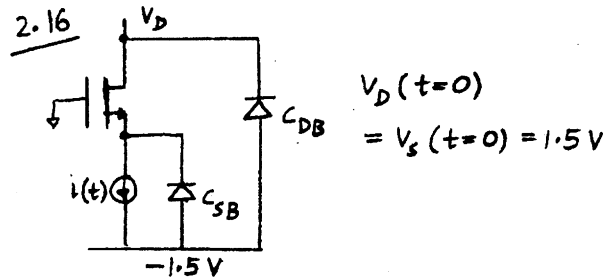
$$= \frac{0.2 \times 10 \times 1 + 1.2 (10 + 1 \times 2)}{\sqrt{1 + (3/0.7)}} \text{ fF}$$

$$= 7.1 \text{ fF}$$

$$(g) C_{sb} = \frac{C_{j0} \times (\text{source area}) + C_{jsw0} \times \text{periphery}}{\sqrt{1 + V_{SB}/\phi_0}}$$

$$= \frac{0.2 \times 10 \times 1 + 1.2 (10 + 1 \times 2)}{\sqrt{1 + (1/0.7)}} \text{ fF}$$

$$= 10.5 \text{ fF}$$



(i) Initially transistor is off, current source discharges $C_{OL} + C_{SB}$. The rate of voltage change is,

$$\frac{V}{t} = \frac{I}{C}$$

$$\approx \frac{10 \mu\text{A}}{0.35 \frac{\text{fF}}{\mu\text{m}} \times 10 \mu\text{m} + 0.2 \frac{\text{fF}}{\mu\text{m}^2} \times 10 \mu\text{m} \times (1 \mu\text{m}) + 0.09 \mu\text{m}) + 1.2 \frac{\text{fF}}{\mu\text{m}} (12 \mu\text{m})}$$

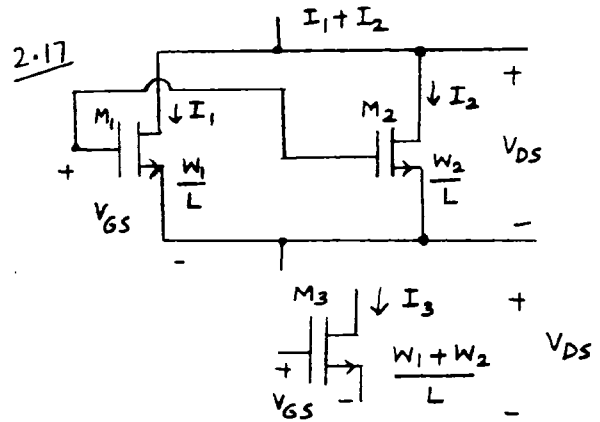
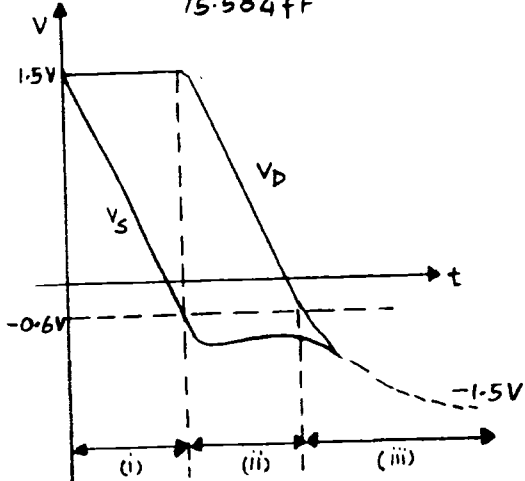
$$= 500 \text{ V}/\mu\text{sec}$$

- (ii) Transistor enters saturation region ; drain current starts to flow, discharges $C_{OL} + C_{DB}$ and $\frac{2}{3} C_{ox} WL + C_{OL} + C_{SB}$. The discharge rate of drain voltage is

$$\begin{aligned} \frac{V}{t} &\cong \frac{10 \mu A}{C_{OL} + C_{DB}} \\ &= \frac{10 \mu A}{0.35 \frac{fF}{\mu m} \times 10 \mu m + 0.2 \frac{fF}{\mu m^2} \times 10 \mu m \times (1 \mu m + 0.09 \mu m) + 1.2 \frac{fF}{\mu m} (12 \mu m)} \\ &= 500 \text{ V}/\mu s \end{aligned}$$

- (iii) Transistor enters triode region, current discharges $C_{ox} WL + C_{DB} + C_{SB} + 2C_{OL}$ at a rate of,

$$\begin{aligned} \frac{V}{t} &\cong \frac{10 \mu A}{\left\{ 4.32(10)(1-2(0.09)) + 0.2(10)(1+0.09)2 + 1.2(12)2 + \underbrace{0.35(2)(10)}_{2 \text{ overlaps}} \right\}} \\ &= \frac{10 \mu A}{75.584 fF} = 132.30 \text{ V}/\mu s \end{aligned}$$



Note that all the transistors have equal terminal voltages. So,

$$V_{GS1} = V_{GS2} = V_{GS3} = V_{GS}$$

$$V_{DS1} = V_{DS2} = V_{DS3} = V_{DS}$$

$$V_{SB1} = V_{SB2} = V_{SB3} = V_{SB}$$

If $V_{SB} \neq 0$, there is a body effect

$$\text{but } V_{t1} = V_{t2} = V_{t3} = V_t$$

Case 1 : All active

$$I_1 = \frac{K'}{2} \frac{W_1}{L} (V_{GS} - V_t)^2 (1 + \lambda V_{DS})$$

$$I_2 = \frac{K'}{2} \frac{W_2}{L} (V_{GS} - V_t)^2 (1 + \lambda V_{DS})$$

$$I_1 + I_2 = \frac{K'}{2} \left(\frac{W_1}{L} + \frac{W_2}{L} \right) (V_{GS} - V_t)^2 (1 + \lambda V_{DS})$$

$$\begin{aligned} I_3 &= \frac{K'}{2} \left(\frac{W_1 + W_2}{L} \right) (V_{GS} - V_t)^2 (1 + \lambda V_{DS}) \\ &= I_1 + I_2 \end{aligned}$$

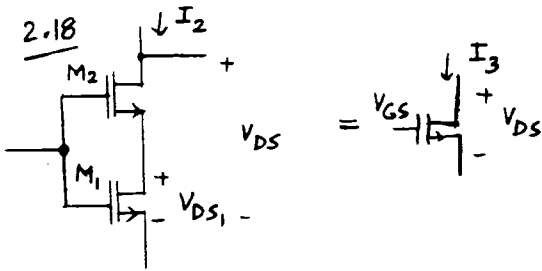
Case 2 : All triode

$$I_1 = \frac{K'}{2} \frac{W_1}{L} [2(V_{GS} - V_t) V_{DS} - V_{DS}^2]$$

$$I_2 = \frac{K'}{2} \frac{W_2}{L} [2(V_{GS} - V_t) V_{DS} - V_{DS}^2]$$

$$I_1 + I_2 = \frac{K'}{2} \left(\frac{W_1}{L} + \frac{W_2}{L} \right) [2(V_{GS} - V_t) V_{DS} - V_{DS}^2]$$

$$\begin{aligned} I_3 &= \frac{K'}{2} \left(\frac{W_1 + W_2}{L} \right) [2(V_{GS} - V_t) V_{DS} - V_{DS}^2] \\ &= I_1 + I_2 \end{aligned}$$



M_2 can operate in active or triode region. M_1 always operates in triode region

$$I_1 = \frac{K'}{2} \left(\frac{W}{L} \right)_1 [2(V_{GS} - V_t)V_{DS1} - V_{DS1}^2] = I_2$$

Solve for V_{DS1} ,

$$V_{DS1}^2 - 2(V_{GS} - V_t)V_{DS1} + \frac{2I_2}{K' \left(\frac{W}{L} \right)_1} = 0$$

$$V_{DS1} = \frac{2(V_{GS} - V_t) \pm \sqrt{4(V_{GS} - V_t)^2 - 4 \frac{2I_2}{K' \left(\frac{W}{L} \right)_1}}}{2}$$

V_{DS1} must be $< V_{GS} - V_t$ or M_1 would be in active region.

$$V_{DS1} = V_{GS} - V_t - \sqrt{(V_{GS} - V_t)^2 - \frac{2I_2}{K' \left(\frac{W}{L} \right)_1}}$$

Assume M_2 is active,

$$\begin{aligned} I_2 &= \frac{K'}{2} \left(\frac{W}{L} \right)_2 (V_{GS} - V_{DS1} - V_t)^2 \\ &= \frac{K'}{2} \left(\frac{W}{L} \right)_2 \left[V_{GS} - V_t - (V_{GS} - V_t) + \sqrt{(V_{GS} - V_t)^2 - \frac{2I_2}{K' \left(\frac{W}{L} \right)_1}} \right]^2 \\ &= \frac{K'}{2} \left(\frac{W}{L} \right)_2 (V_{GS} - V_t)^2 - \left(\frac{W}{L} \right)_2 \frac{I_2}{\left(\frac{W}{L} \right)_1} \end{aligned}$$

$$I_2 \left(1 + \left(\frac{W}{L} \right)_2 / \left(\frac{W}{L} \right)_1 \right) = \frac{K'}{2} \left(\frac{W}{L} \right)_2 (V_{GS} - V_t)^2$$

$$\begin{aligned} I_2 &= \left[\frac{K'}{2} \left\{ \left(\frac{W}{L} \right)_2 / 1 + \left(\frac{W}{L} \right)_2 / \left(\frac{W}{L} \right)_1 \right\} \right] (V_{GS} - V_t)^2 \\ &= \frac{K'}{2} \left(\frac{W}{L_1 + L_2} \right) (V_{GS} - V_t)^2 \end{aligned}$$

If M_2 and M_3 are active,

$$I_3 = \frac{K'}{2} \left(\frac{W}{L_1 + L_2} \right) (V_{GS} - V_t)^2 = I_2$$

Assume M_2 is in triode region,

$$I_2 = \frac{K'}{2} \left(\frac{W}{L} \right)_2 \left[2(V_{GS} - V_{DS1} - V_t)(V_{DS} - V_{DS1}) - (V_{DS} - V_{DS1})^2 \right]$$

$$V_{DS1} = V_{GS} - V_t - \sqrt{(V_{GS} - V_t)^2 - \frac{2I_2}{K' \left(\frac{W}{L} \right)_1}}$$

$$\begin{aligned} I_2 &= \frac{K'}{2} \left(\frac{W}{L} \right)_2 \left[2 \sqrt{(V_{GS} - V_t)^2 - \frac{2I_2}{K' \left(\frac{W}{L} \right)_1}} \left[V_{DS} - (V_{GS} - V_t) + \sqrt{(V_{GS} - V_t)^2 - \frac{2I_2}{K' \left(\frac{W}{L} \right)_1}} \right] - \left[V_{DS} - (V_{GS} - V_t) + \sqrt{(V_{GS} - V_t)^2 - \frac{2I_2}{K' \left(\frac{W}{L} \right)_1}} \right]^2 \right] \end{aligned}$$

Let $X = V_{DS} - (V_{GS} - V_t)$ and

$$Y = \sqrt{(V_{GS} - V_t)^2 - \frac{2I_2}{K' \left(\frac{W}{L} \right)_1}}$$

Then,

$$I_2 = \frac{K'}{2} \left(\frac{W}{L} \right)_2 \left[2Y(X+Y) - (X+Y)^2 \right]$$

$$I_2 = \frac{K'}{2} \left(\frac{W}{L} \right)_2 \left[2XY + 2Y^2 - X^2 - Y^2 - 2XY \right]$$

$$\begin{aligned} I_2 &= \frac{K'}{2} \left(\frac{W}{L} \right)_2 \left[Y^2 - X^2 \right] \\ &= \frac{K'}{2} \left(\frac{W}{L} \right)_2 \left[(V_{GS} - V_t)^2 - \frac{2I_2}{K' \left(\frac{W}{L} \right)_1} - \{ V_{DS} - (V_{GS} - V_t) \}^2 \right] \end{aligned}$$

$$\begin{aligned} &= \frac{K'}{2} \left(\frac{W}{L} \right)_2 \left[(V_{GS} - V_t)^2 - \frac{2I_2}{K' \left(\frac{W}{L} \right)_1} - V_{DS}^2 + 2V_{DS}(V_{GS} - V_t) - (V_{GS} - V_t)^2 \right] \end{aligned}$$

$$I_2 \left(1 + \left(\frac{W}{L} \right)_2 / \left(\frac{W}{L} \right)_1 \right) = \frac{K'}{2} \left(\frac{W}{L} \right)_2 \left\{ -V_{DS}^2 + 2V_{DS}(V_{GS} - V_t) \right\}$$

$$\begin{aligned} I_2 &= \frac{K'}{2} \frac{W}{L_1 + L_2} \left[2(V_{GS} - V_t)V_{DS} - V_{DS}^2 \right] \\ &= I_3 \end{aligned}$$

2.19(a) curve B ;(i) The cost of a 40,000 mil² chip is

$$C = \frac{C_w}{(NY_{ws}) Y_{df} Y_{ft}} = \frac{100}{(47)(10.9)(0.8)} + \frac{0.6}{0.8}$$

$$= 3.71$$

 $NY_{ws} = 47$ is obtained from fig.(2.70)(ii) The cost of two 20,000 mil² chips is,

$$C_{Y_2} = \frac{100}{(200)(0.9)(10.8)} + \frac{0.6}{0.8} = 1.44$$

$$C_{total} = C_{1/2} \times 2 = 2.88$$

∴ Putting the system on two chips is more economical

(b) curve A ;(i) For a 40,000 mil² chip,

$$C = \frac{100}{(115)(0.9)(0.8)} + \frac{0.6}{0.8} = 1.1$$

$$C_{total} = 1.1 \times 2 = 2.2$$

∴ one chip is more economical.

(c) curve C ;(i) For a 40,000 mil² chip,

$$C = \frac{100}{12(0.9)(0.8)} + \frac{0.6}{0.8} = 12.3$$

(ii) For two 20,000 mil² chips,

$$C_{1/2} = \frac{100}{(80)(0.9)(0.8)} + \frac{0.6}{0.8} = 2.49$$

$$C_{total} = 2.49 \times 2 = 4.98$$

∴ using two chips is more economical.

2.20

$$\text{Area} = (150 \text{ mils})^2 = 22,500 \text{ mil}^2$$

(a) curve A ,

$$C = \frac{C_w}{(NY_{ws})(Y_{df})(Y_{ft})} + \frac{C_p}{Y_{ft}}$$

$$= \frac{130}{(360)(0.8)(0.8)} + \frac{0.4}{0.8} = 1.06$$

$NY_{ws} = 360$ is obtained from Fig.(2.70)

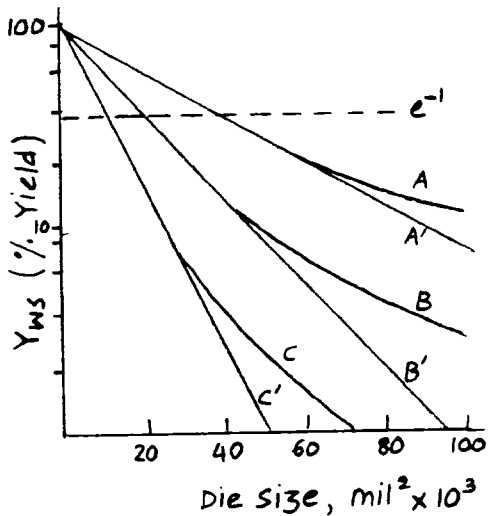
(b) curve B,

$$C = \frac{130}{(140)(0.8)(0.8)} + \frac{0.4}{0.8} = 1.95$$

(c) curve C ,

$$C = \frac{130}{(60)(0.8)(0.8)} + \frac{0.4}{0.8} = 3.89$$

2.21

(a) When $Y_{ws} = e^{-1} = 0.37$ From curve A, $A_0 = 38,000 \text{ mil}^2$ Curve B, $A_0 = 20,000 \text{ mil}^2$ Curve C, $A_0 = 11,000 \text{ mil}^2$ 

Curves A', B' and C' are predicted by the equation.

(b) In fig (2.69), gross die/wafer is inversely proportional to the die size, i.e., $N = KA^{-1}$, K is the proportionality constant related to the wafer size (more specifically, K is the effective or usable area on the wafer). By (2.56), the cost per unit silicon area is,

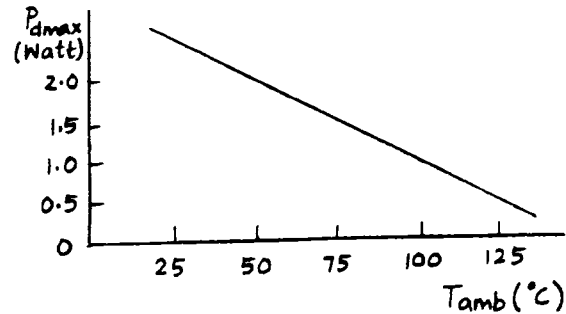
$$\frac{C}{A} = \frac{C_w}{A N Y_{ws} Y_{df} Y_{ft}} + \frac{C_p}{A Y_{ft}}$$

$$= \frac{C_w}{K e^{-1/A_0} Y_{df} Y_{ft}} + \frac{C_p}{A Y_{ft}}$$

Each K can be obtained from fig (2.69). e.g. $K \approx 1.15 \times 10^5 \text{ mil}^2$ for 4" wafer.

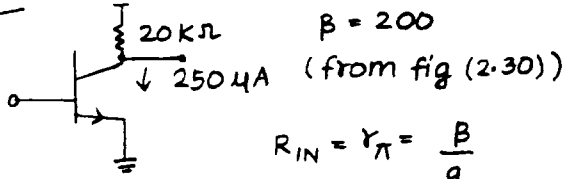
2.22 The total thermal resistance is 50°C/Watt .

$$P_{dmax} = \frac{150^\circ\text{C} - T_{ambient}}{50^\circ\text{C/W}}$$



CHAPTER 3

3.1



$$\beta = 200 \quad (\text{from fig (2.30)})$$

$$R_{IN} = r_{\pi} = \frac{\beta}{g_m}$$

$$= 100 \Omega \times 200$$

$$= 20.8 \text{ k}\Omega$$

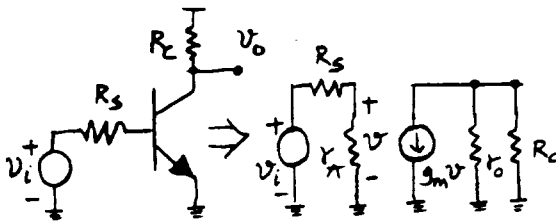
$$G_m = g_m = \frac{I_c}{V_T} = \frac{1}{104} \text{ A/V}$$

$$R_o = R_c \parallel r_o = 200 \text{ k} \parallel \frac{1}{\eta g_m}$$

$$= 20 \text{ k} \parallel \frac{104 \Omega}{2 \times 10^4} = 20 \text{ k} \parallel 520 \text{ k}$$

$$= 19.3 \text{ k}\Omega$$

3.2



$$A_v = \left(\frac{r_{\pi}}{R_s + r_{\pi}} \right) g_m (r_o \parallel R_c)$$

$$= \frac{\beta (r_o \parallel R_c)}{r_s + r_{\pi}} = \beta \left(\frac{V_A}{I_c} \parallel R_c \right)$$

Now, when

$$I_c \rightarrow \infty, A_v \rightarrow 0 \text{ because } R_c \rightarrow 0$$

$$I_c \rightarrow 0, A_v \rightarrow 0 \text{ because } g_m \rightarrow 0$$

$$A_v = \beta \left(\frac{\frac{V_A R_c}{I_c}}{\frac{V_A}{I_c} + R_c} \right) \left(\frac{1}{R_s + \frac{\beta V_T}{I_c}} \right)$$

$$= \beta \left(\frac{I_c R_c}{1 + \frac{I_c R_c}{V_A}} \right) \left(\frac{1}{R_s I_c + \beta V_T} \right)$$

$$\therefore A_v = \beta \left[\frac{\left(\frac{I_c R_c}{\beta V_T} \right)}{\left(1 + \frac{I_c R_c}{V_A} \right) \left(1 + \frac{R_s I_c}{\beta V_T} \right)} \right]$$

$$\frac{\partial A_v}{\partial I_c} = 0$$

$$\therefore 1 - \left(\frac{\frac{I_c R_c}{V_A}}{1 + \frac{I_c R_c}{V_A}} \right) - \left(\frac{\frac{I_c R_c}{\beta V_T}}{1 + \frac{I_c R_c}{\beta V_T}} \right) = 0$$

$$1 - \frac{ax}{1+ax} - \frac{bx}{1+bx} = 0$$

$$\text{Where } a = \frac{R_c}{V_A}, b = \frac{R_s}{\beta V_T}, x = I_c$$

$$(1+ax)(1+bx) - (1+bx)ax - (1+ax)bx = 0$$

$$\therefore \left(1 + \frac{I_c R_c}{V_A} \right) \left(1 + \frac{I_c R_s}{\beta V_T} \right) - \left(1 + \frac{I_c R_s}{\beta V_T} \right) \left(\frac{I_c R_c}{V_A} \right) - \left(1 + \frac{I_c R_c}{V_A} \right) \left(\frac{I_c R_s}{\beta V_T} \right) = 0$$

$$\therefore 1 - \left(\frac{I_c R_c}{V_A} \right) \left(\frac{I_c R_s}{\beta V_T} \right) = 0$$

$$I_c^2 \left(\frac{R_c}{V_A} \right) \left(\frac{R_s}{\beta V_T} \right) = 1$$

$$\therefore I_{c \text{ opt.}} = \sqrt{\left(\frac{V_A}{R_c} \right) \left(\frac{\beta V_T}{R_s} \right)}$$

$$A_{v \text{ opt.}} = \beta \left(\frac{I_{c \text{ opt.}} R_c}{\beta V_T} \right) \left(\frac{1}{\left(1 + \frac{I_{c \text{ opt.}} R_c}{V_A} \right) \left(1 + \frac{I_{c \text{ opt.}} R_s}{\beta V_T} \right)} \right)$$

$$= \beta \left(\frac{\sqrt{V_A/R_s}}{\sqrt{\beta V_T/R_c}} \right) \left[\frac{1}{\left(1 + \frac{\sqrt{\beta V_T/R_s}}{\sqrt{V_A/R_c}} \right) \left(1 + \frac{\sqrt{V_A/R_c}}{\sqrt{\beta V_T/R_c}} \right)} \right]$$

$$\text{Let } x' = \sqrt{\left(\frac{V_A}{\beta V_T} \right) \left(\frac{R_s}{R_c} \right)}$$

Then,

$$A_{v \text{ opt.}} = \beta x' \left[\frac{1}{\left(1 + \frac{1}{x'} \right) \left(1 + x' \right)} \right] \left(\frac{R_c}{R_s} \right)$$

3.3

$$R_S = 50 \text{ k}\Omega, R_C = 50 \text{ k}\Omega, \beta = 200$$

$$V_A = 120 \text{ V}$$

$$I_{C_{OPT.}} = \sqrt{\left(\frac{120 \text{ V}}{50 \text{ k}\Omega}\right) \left(\frac{26 \text{ mV} \times 200}{50 \text{ k}\Omega}\right)} = 0.5 \text{ mA}$$

$$A_{v_{OPT.}} = (200) x' \left[\frac{1}{\left(1 + \frac{1}{x'}\right) \left(1 + x'\right)} \right] \times \frac{50 \text{ k}}{50 \text{ k}}$$

$$\text{Where, } x' = \sqrt{\left(\frac{V_A}{\beta V_T}\right) \left(\frac{R_S}{R_C}\right)} = 4.8$$

$$\therefore A_{v_{OPT.}} = 200 \times 4.8 \times \left[\frac{1}{\left(1 + \frac{1}{4.8}\right) \left(1 + 4.8\right)} \right] = 137$$

$$\text{DC voltage on RC} = 0.5 \times 50 = 25 \text{ V}$$

3.4

$$V_O = V_{DD} - R_D \frac{\mu C_{ox}}{2} \frac{W}{L} (V_{GS} - V_t)^2$$

$$\text{Triode edge } V_{DS} = V_{GS} - V_t = V_O$$

$$V_{DS} = V_{DD} - R_D \frac{\mu C_{ox}}{2} \frac{W}{L} V_{DS}^2$$

$$V_{DS} = 3 - \frac{5 \text{ K}}{2} (200 \mu) (10) V_{DS}^2$$

$$5 V_{DS}^2 + V_{DS} - 3 = 0$$

$$V_{DS} = \frac{-1 + \sqrt{61}}{10} = 0.0681 \text{ V} = V_O$$

$$0.681 \text{ V} = V_{GS} - V_t = V_i - V_t$$

$$0.681 = V_i - 0.6$$

$$1.281 = V_i$$

$$\text{s.s. } \frac{V_O}{V_i} = -g_m R_D = -6.81$$

$$g_m = k' \frac{W}{L} (V_{GS} - V_t) = 200 \mu (10) (0.681) = 1.36 \frac{\text{mA}}{\text{V}}$$

$$\text{unity gain } g_m R_D = 1,$$

$$g_m = \frac{1}{R_D} = \frac{1}{5 \text{ K}} = 200 \mu (10) (V_{GS} - V_t)$$

$$0.1 = V_{GS} - V_t$$

$$0.1 + 0.6 = 0.7 \text{ V} = V_i$$

$$I_D = \frac{200 \mu (10) (0.1)^2}{2} = 10 \mu \text{ A}$$

$$V_O = 3 - 10 \mu \text{ A} (5 \text{ k}\Omega) = 2.95 \text{ V}$$

In active region:

$$g_m = k' \frac{W}{L} (V_{GS} - V_t)$$

$$g_m = \sqrt{2 k' \frac{W}{L} I_D}$$

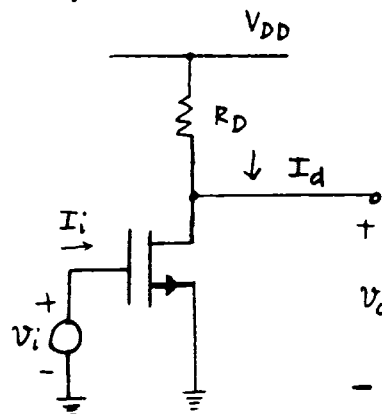
get maximum g_m at max. I_D just before I_D gets large enough to bring mosfet in linear region.

In linear region:

$$g_m = k' \frac{W}{L} (V_{DS}) \text{ which decreases as } I_D \text{ increases}$$

So, the maximum g_m occurs at the edge between active and linear regions.

$$\frac{V_O}{V_i} = -6.81 = \text{maximum gain}$$



COMMON SOURCE GAIN STAGE, MAX GAIN

```

VDD 100 0 3
M1 2 1 0 0 NMOS W=10U L=1U
RD 100 2 5K
VI 1 0 1.281
.MODEL NMOS NMOS LEVEL=1 VTO=0.6 KP=200U LAMBDA=0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF V(2) VI
.OP
.END

```

```

**** OPERATING POINT INFORMATION THOM= 27 TEMP= 27
      NODE =VOLTAGE      NODE =VOLTAGE      NODE =VOLTAGE
+0:1   = 1.281E+00 0:2   = 6.812E-01 0:100 = 3.000E+00

```

**** MOSFETS

SUBCKT

```

ELEMENT 0:M1
MODEL 0:NMOS
ID 4.638E-04
IBS 0.
IBD -6.812E-15
VGS 1.281E+00
VDS 6.812E-01
VBS 0.
VTH 6.000E-01
VDSAT 6.810E-01
BETA 2.000E-03
GAM EFF 0.
GM 1.362E-03
GDS 0.

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(2)/VI = -6.810E+00
INPUT RESISTANCE AT VI = 1.000E+20
OUTPUT RESISTANCE AT V(2) = 5.000E+03

```

COMMON SOURCE GAIN STAGE, UNITY GAIN

```

VDD 100 0 3
M1 2 1 0 0 NMOS W=10U L=1U
RD 100 2 5K
VI 1 0 0.7
.MODEL NMOS NMOS LEVEL=1 VTO=0.6 KP=200U LAMBDA=0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF V(2) VI
.OP
.END

```

```

**** OPERATING POINT INFORMATION THOM= 27 TEMP= 27
      NODE =VOLTAGE      NODE =VOLTAGE      NODE =VOLTAGE
+0:1   = 7.000E-01 0:2   = 2.950E+00 0:100 = 3.000E+00

```

SUBCKT

```

ELEMENT 0:M1
MODEL 0:NMOS
ID 1.000E-05
IBS 0.
IBD -2.950E-14
VGS 7.000E-01
VDS 2.950E+00
VBS 0.
VTH 6.000E-01
VDSAT 1.000E-01
BETA 2.000E-03
GAM EFF 0.
GM 2.000E-04
GDS 0.

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(2)/VI = -1.000E-00
INPUT RESISTANCE AT VI = 1.000E+20
OUTPUT RESISTANCE AT V(2) = 5.000E+03

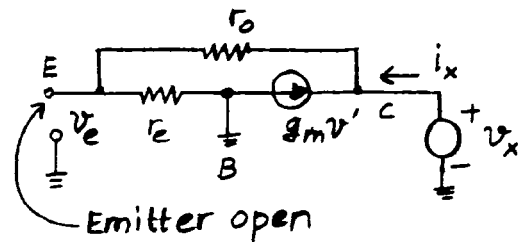
```

3.5

$$R_i = r_e \approx \frac{1}{g_m} = \frac{V_T}{I_c} = 104 \Omega$$

$$R_o = R_c = 10 \text{ k}\Omega$$

$$G_m = g_m = \frac{1}{104} \text{ A/V}$$

3.6Driven by current source:

$$v_e = v_x \left(\frac{r_e}{r_o + r_e} \right)$$

$$i_x = \frac{v_x}{r_o + r_e} - g_m v_e$$

$$= v_x \left[\frac{1}{r_o + r_e} - \frac{g_m r_e}{r_o + r_e} \right]$$

$$\therefore \frac{i_x}{v_x} = \frac{1}{R_o} = \frac{1 - g_m r_e}{r_o + r_e}$$

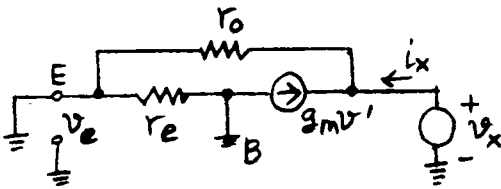
$$\text{But, } g_m r_e = \alpha_F = \frac{\beta_F}{1 + \beta_F}$$

$$\therefore \frac{i_x}{v_x} = \frac{1 - \frac{\beta_F}{1 + \beta_F}}{r_o + r_e} = \frac{1}{(1 + \beta_F)(r_o + r_e)}$$

Now, $r_o \gg r_e$ and $\beta_F \gg 1$, so

$$\frac{v_r}{i_r} = R_o = \beta_F R_o$$

For common-base driven from voltage source:

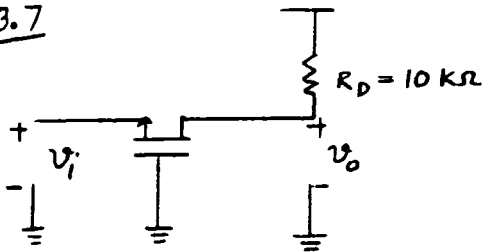


v_e is zero, since emitter shorted to ground for small signals.

$$\text{Thus, } \frac{v_x}{i_x} = R_o = r_o$$

Thus, we get much higher r_o when the CE stage is driven from a high source resistance.

3.7



From (3.54) $\rightarrow$ (without R_L and g_{mb}),

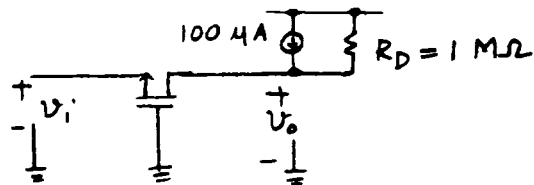
$$R_i = \frac{r_o + R_D}{1 + g_m r_o}$$

$$r_o = \frac{1}{\lambda I_D} = \frac{1}{(0.01)(100\mu)} = 1\text{M}\Omega$$

$$g_m = \sqrt{2K' \left(\frac{W}{L}\right) I_D} = \sqrt{2(200) \left(\frac{100}{1}\right) 100} = 2000\text{ }\mu\text{A/V}$$

$$g_m r_o = 2000$$

$$R_i = \frac{1\text{M}\Omega + 10\text{k}\Omega}{2001} \approx \frac{1\text{M}\Omega}{2000} = \frac{1}{g_m} = 500\Omega$$



$$R_i \approx \frac{1\text{M}\Omega + 1\text{M}\Omega}{2001} \approx 1000\Omega$$

3.8

$$\begin{aligned} R_i &= r_{\pi} + R_L (1 + \beta) \\ &= 200 \times 26\Omega + 500 \times 201\Omega \\ &= 105.7\text{ k}\Omega \end{aligned}$$

$$\begin{aligned} R_o &= \left(\frac{R_s}{1 + \beta} + \frac{1}{g_m} \right) \parallel R_L \\ &= \left(\frac{5\text{k}}{201} + 26 \right) \parallel 500 \\ &= 51 \parallel 500 \\ &= 46\Omega \end{aligned}$$

$$\begin{aligned} \text{Voltage gain} &= \frac{1}{1 + \frac{R_s + r_{\pi}}{(1 + \beta)R_L}} \\ &= \frac{1}{1 + \frac{5.0\text{k} + 5.2\text{k}}{(201)(500)}} \\ &= 0.91 \end{aligned}$$

3.9

$$\textcircled{a} \quad V_o = 3 - V_t - (V_{GS} - V_t)$$

$$V_{GS} - V_t = \sqrt{\frac{2I}{K'W_L}}; \quad K' = \mu_n C_{ox}'$$

$$C_{ox}' = \frac{3.9 \times 8.854 \times 10^{-14}}{250 \times 10^{-8} \text{ cm}} = 1.38 \frac{\text{fF}}{\mu^2}$$

$$K' = \frac{650 \frac{\text{cm}^2}{\text{V}\cdot\text{s}} \cdot 1.38 \times 10^{-7} \frac{\text{F}}{\text{cm}}}{\text{V}\cdot\text{s}} = 89.7 \mu\text{A}/\text{V}^2 \approx 90 \mu\text{A}/\text{V}^2$$

$$\therefore V_{GS} - V_t = \sqrt{\frac{2(200)}{90(10)}} \approx 0.67 \text{ V}$$

$$\Rightarrow V_o = 3 - 0.7 - 0.67 = 1.63 \text{ V}$$

$$\frac{V_o}{V_i} = \frac{g_m r_o}{1 + g_m r_o}; \quad r_o = \infty \text{ since } \lambda = 0$$

$$\Rightarrow \frac{V_o}{V_i} = 1$$

$\textcircled{b}$ V_t affects V_o and vice-versa, solve iteratively,

$$V_t = V_{t0} + \gamma \left(\sqrt{2\phi_F + V_{SB}} - \sqrt{2\phi_F} \right)$$

$$\gamma = \frac{\sqrt{2q\epsilon N_A}}{C_{ox}'}$$

$$\Rightarrow \gamma = \frac{\sqrt{2(1.6 \times 10^{-19})(11.7 \times 8.854 \times 10^{-14})(2 \times 10^{15})}}{1.38 \times 10^{-7}}$$

$$= 0.19 \sqrt{\text{V}}$$

$$V_{SB} = V_o - (\text{use ans. from (a) to start})$$

$$\phi_F = V_T \ln \frac{N_A}{N_i} = (26 \text{ mV}) \ln \frac{2 \times 10^{15}}{1.5 \times 10^{10}} \approx 0$$

$$V_t = 0.7 + 0.19 \left[\sqrt{0.6 + 1.63} - \sqrt{0.6} \right] = 0.84 \text{ V}$$

$$\text{So, } V_o = 3 - 0.84 - 0.6 = 1.49$$

(Try again)

$$V_t = 0.7 + 0.19 \left[\sqrt{0.6 + 1.63} - \sqrt{0.6} \right] = 0.83$$

(Not much change)

$$\text{So, } V_o = 3 - 0.83 - 0.67 \approx 1.5 \text{ V}$$

$$\frac{V_o}{V_i} = \frac{g_m}{g_m + g_{mb}} = \frac{1}{1 + \chi}$$

$$\chi = \frac{0.19}{2\sqrt{0.6 + 1.5}} \approx 0.07$$

$$\Rightarrow \frac{V_o}{V_i} = \frac{1}{1 + 0.07} \approx 0.93$$

$\textcircled{c}$ Use V_o from (b) at first

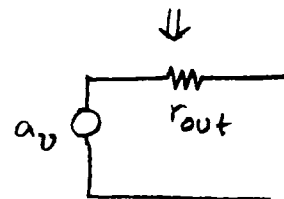
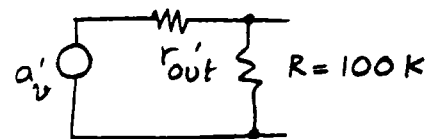
$$\Rightarrow I = 200 \mu\text{A} + \frac{1.5}{100 \text{ k}} \approx 215 \mu\text{A}$$

$$V_o = 3 - 0.83 - \sqrt{\frac{2(215)}{90 \cdot 10}} = 1.48 \text{ V}$$

(Not much change from (b) so don't bother to recalculate V_t)

To find $a_v = \frac{v_o}{v_i}$, use

$$a_{v'} = \text{OCVG from (b)} = 0.93$$



$$a_v = a_{v'} \frac{100 \text{ k}}{100 \text{ k} + r_{out}'}$$

$$r_{out}' = \frac{1}{(g_m + g_{mb})} = \frac{1}{g_m(1+x)}$$

$$g_m = \sqrt{2(215)90.10} = 0.6 \text{ mA/V}$$

$$r_{out}' = \frac{1}{(0.62)(1.07)} = 1.5 \text{ k}\Omega$$

$$\Rightarrow a_v = 0.93 \frac{100}{101.5} = 0.92$$

④ Use V_o from (c) at first,

$$I = 200 + \frac{1.48}{10 \text{ k}} = 348 \text{ }\mu\text{A}$$

$$V_o = 3 - 0.83 - \sqrt{\frac{2(348)}{90.10}} = 1.29 \text{ V}$$

$$V_t = 0.7 + 0.19 \left(\sqrt{0.6 + 1.29} - \sqrt{0.6} \right) = 0.81 \text{ V}$$

$$I = 200 + \frac{1.29}{10 \text{ k}} = 329 \text{ }\mu\text{A}$$

$$V_o = 3 - 0.81 - \sqrt{\frac{2(329)}{90.10}} = 1.33 \text{ V}$$

$$a_v' = \frac{1}{1+x}; \quad x = \frac{0.19}{2(\sqrt{0.6+1.33})} \approx 0.07$$

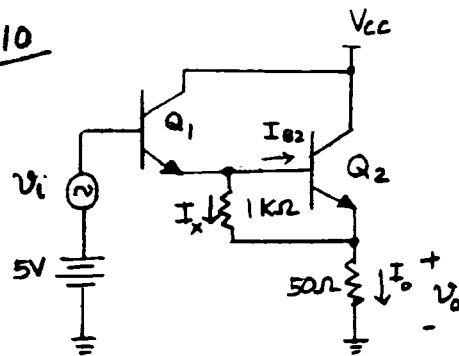
$$\Rightarrow a_v' \approx 0.93$$

$$r_{out}' = \frac{1}{[g_m(1+x)]}; \quad g_m = \sqrt{2(329)90(10)} = 0.77 \text{ mA/V}$$

$$r_{out}' = \frac{1}{0.77(1.07)} = 1.2 \text{ k}\Omega$$

$$\Rightarrow a_v = 0.93 \frac{10 \text{ k}}{11.2 \text{ k}} = 0.83$$

3.10



The DC voltage across the 50Ω resistor is,

$$V_o = 5 - 0.7 - 0.7 = 3.6 \text{ V}$$

$$\text{Thus, } I_o = \frac{3.6 \text{ V}}{50\Omega} = 72 \text{ mA}$$

The current I_x is,

$$I_x = \frac{0.7 \text{ V}}{1 \text{ k}\Omega} = 0.7 \text{ mA}$$

The emitter current of Q_2 is

$$I_{E2} = I_o - I_x = 71.3 \text{ mA}$$

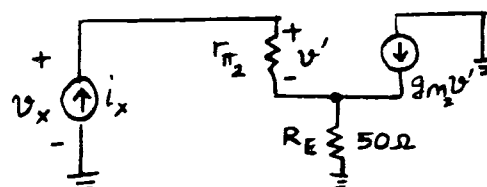
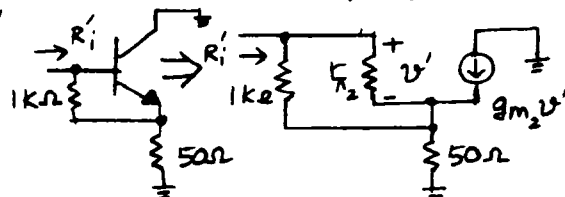
The base current of Q_2 is,

$$I_{B2} = \frac{I_{E2}}{1+\beta} = \frac{71.3}{201} = 0.35 \text{ mA}$$

Thus, the emitter current of Q_1 is

$$I_{E1} = I_x + I_{B2} = 0.7 + 0.35 = 1.05 \text{ mA}$$

calculation of R_i :



$$v_x = i_x r_{\pi_2} + (i_x + g_{m_2} r_{\pi_2} i_x) R_E$$

$$\frac{v_x}{i_x} = r_{\pi_2} + (1 + g_{m_2} r_{\pi_2}) R_E$$

Now, the $1\text{ k}\Omega$ resistor is connected in parallel with r_{π_2} , so define a new effective r_{π_2} ,

$$r_{\pi_2}' = r_{\pi_2} \parallel 1\text{ k}$$

$$R_i' = (r_{\pi_2} \parallel 1\text{ k}) + [1 + g_{m_2} (r_{\pi_2} \parallel 1\text{ k})] R_E$$

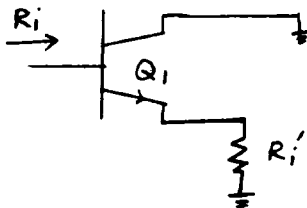
$$r_{\pi_2} = \frac{\beta}{g_{m_2}} = 200 \times \frac{26\text{ mV}}{71\text{ mA}} = 73\ \Omega$$

$$r_{\pi_2}' = 73 \parallel 1\text{ k} = 68\ \Omega$$

$$\therefore R_i' = 68\ \Omega + \left[1 + \left(\frac{71\text{ mA}}{26\text{ mV}}\right)(68\ \Omega)\right] 50\ \Omega$$

$$= 9.4\ \text{k}\Omega$$

Now consider R_i



$$R_i = r_{\pi_1} + (1 + \beta) R_i'$$

$$= 200 \left(\frac{26\text{ mV}}{1.05\text{ mA}} \right) + (201)(9.4\ \text{k}\Omega)$$

$$= (4.95\ \text{k} + 1.88\ \text{M})\ \Omega$$

$$= 1.89\ \text{M}\Omega$$

calculation of voltage gain,

(a) gain from input to emitter of Q_1 (use Eq. (3.20))

$$A_{v_1} = \frac{1}{1 + \frac{r_{\pi_1}}{(1 + \beta) R_i'}}$$

$$A_{v_1} = \frac{1}{1 + \frac{r_{\pi_1}}{(1 + \beta) R_i'}} = \frac{1}{1 + \frac{4.9\ \text{k}}{(201)(9.4\ \text{k})}}$$

$$= 0.997$$

(b) Gain from base of Q_2 to output. Use Eq. (3.20), substitute $g_m r_{\pi}'$ for β_0

$$A_{v_2} = \frac{1}{1 + \frac{r_{\pi_2}'}{(1 + g_m r_{\pi}') R_L}}$$

$$= \frac{1}{1 + \frac{68\ \Omega}{\left[68\ \Omega \left(\frac{71\text{ mA}}{26\text{ mV}}\right) + 1\right] 50\ \Omega}}$$

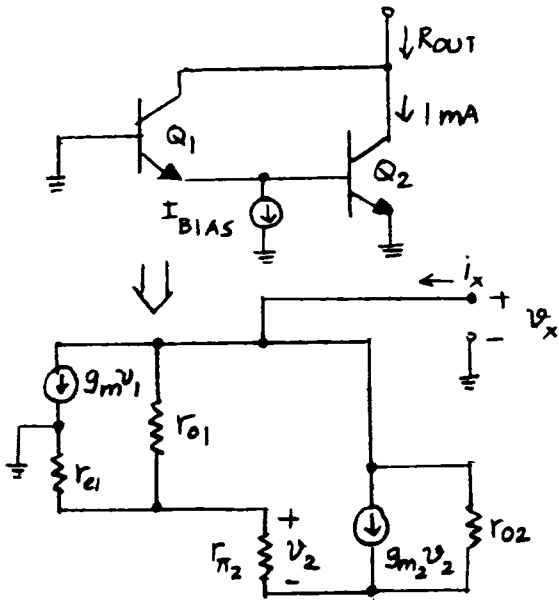
$$= 0.993$$

voltage gain = $0.997 \times 0.993 = 0.990$

DARLINGTON EMITTER FOLLOWER

```
*****
VCC 100 0 10
Q1 100 1 2 NPN
Q2 100 2 3 NPN
R1 2 3 1K
R2 3 0 50
VI 1 0 5
.MODEL NPN NPN IS=1E-14 BF=200 RB=0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF V(3) VI
.OP
.END
**** OPERATING POINT INFORMATION THOM= 27 TEMP= 27
      NODE =VOLTAGE      NODE =VOLTAGE      NODE =VOLTAGE
+0:1 = 5.000E+00 0:2 = 4.342E+00 0:3 = 3.577E+00
+0:100 = 1.000E+01
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT 0:Q1 0:Q2
MODEL 0:NPN 0:NPN
IB 5.558E-06 3.521E-04
IC 1.112E-03 7.042E-02
VBE 6.578E-01 7.651E-01
VCE 5.657E+00 6.423E+00
VBC -5.000E+00 -5.657E+00
VS -1.000E+01 -1.000E+01
POWER 6.293E-03 4.526E-01
BETAD 2.000E+02 2.000E+02
GM 4.298E-02 2.722E+00
RPI 4.653E+03 7.345E+01
RX 0. 0.
RO 5.000E+14 5.657E+14
BETAC 2.000E+02 2.000E+02
**** SMALL-SIGNAL TRANSFER CHARACTERISTICS
V(3)/VI = 9.903E-01
INPUT RESISTANCE AT VI = 1.900E+06
OUTPUT RESISTANCE AT V(3) = 4.842E-01
```


3.11



$$v_2 = -v_1 = v_x \left[\frac{r_{e1} \parallel r_{\pi 2}}{r_{o1} + r_{e1} \parallel r_{\pi 2}} \right]$$

Assume $r_{o1} \gg r_{e1} \parallel r_{\pi 2}$

$$i_x = g_{m1} v_1 + g_{m2} v_2 + \frac{v_x}{r_{o1} + (r_{e1} \parallel r_{\pi 2})} + \frac{v_x}{r_{o2}}$$

$$\frac{i_x}{v_x} = -g_{m1} \left(\frac{r_{e1} \parallel r_{\pi 2}}{r_{o1}} \right) + g_{m2} \left(\frac{r_{e1} \parallel r_{\pi 2}}{r_{o1}} \right) + \frac{1}{r_{o1}} + \frac{1}{r_{o2}}$$

$$= \frac{1}{r_{o2}} + \frac{1}{r_{o1}} \left[1 + (g_{m2} - g_{m1}) (r_{e1} \parallel r_{\pi 2}) \right]$$

$$R_o = \left\{ \frac{1}{r_{o2}} + \frac{1}{r_{o1}} \left[1 + (g_{m2} - g_{m1}) (r_{e1} \parallel r_{\pi 2}) \right] \right\}^{-1}$$

① If $I_{BIAS} = 1 \text{ mA}$, then $g_{m1} \approx g_{m2}$

$$R_o = \left(\frac{1}{r_{o1}} + \frac{1}{r_{o2}} \right)^{-1}$$

② If $I_{BIAS} = 0$, then $I_{C1} = \frac{I_{C2}}{\beta}$ $\therefore r_{e1} \approx r_{\pi 2}, g_{m2} \gg g_{m1}$

$$R_o = \left\{ \frac{1}{r_{o2}} + \frac{1}{r_{o1}} \left[1 + g_{m2} \frac{r_{\pi 2}}{2} \right] \right\}^{-1}$$

But, $r_{o1} = \beta r_{o2}$ (if $I_{C1} = I_{C2}/\beta$)

Thus,

$$R_o = \left\{ \frac{1}{r_{o2}} + \frac{1}{\beta r_{o2}} \left[1 + \frac{\beta}{2} \right] \right\}^{-1} \\ \approx \left(\frac{1}{r_{o2}} + \frac{1}{2 r_{o2}} \right)^{-1} = \frac{2}{3} r_{o2}$$

3.12

$$V_o = 2 \text{ V dc}$$

$$I_C + I_D = 1 \text{ mA}$$

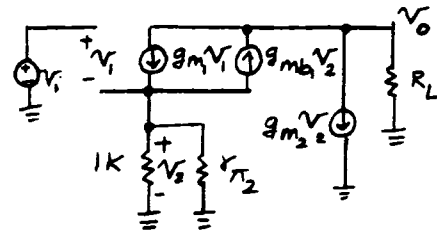
$$I_D \approx \frac{0.1}{1 \text{ K}} = 0.7 \text{ mA}$$

$$I_C \approx 0.3 \text{ mA}$$

$$V_{BE} = V_T \ln \frac{0.3 \text{ mA}}{10^{-16} \text{ A}} = 0.75 \text{ V}$$

$$I_D = 0.75 \text{ mA}$$

$$I_C = 0.25 \text{ mA}$$



$$v_o = (g_{mb1} v_2 - g_{m1} v_1 - g_{m2} v_2) R_L$$

$$v_i = v_1 + v_2$$

$$g_{m1} v_1 - g_{mb1} v_2 = \frac{v_2}{R}$$

$$R = 1 \text{ K} \parallel r_{\pi 2} = 912 \Omega$$

$$r_{\pi 2} = \frac{\beta}{g_{m2}} = \frac{100}{\frac{0.25}{26}} = 10.4 \text{ k}\Omega$$

$$g_{m1} v_1 = v_2 \left(g_{mb1} + \frac{1}{R} \right)$$

$$\frac{v_1}{v_2} = \frac{g_{mb1} + \frac{1}{R}}{g_{m1}}$$

$$v_i = v_2 + v_2 \frac{g_{m1} + g_{mb1} + \frac{1}{R}}{g_{m1}}$$

$$v_2 = v_i \frac{g_{m1}}{g_{m1} + g_{mb1} + \frac{1}{R}}$$

$$v_i = v_i \frac{g_{mb1} + \frac{1}{R}}{g_{m1} + g_{mb1} + \frac{1}{R}}$$

$$v_o = [(g_{mb1} - g_{m2})v_2 - g_{m1}v_i] R_L$$

$$\frac{v_o}{v_i} = \frac{(g_{mb1} - g_{m2})g_{m1} - g_{m1}(g_{mb1} + \frac{1}{R})}{(g_{m1} + g_{mb1} + \frac{1}{R})} R_L$$

$$= \frac{-g_{m1}g_{m2} - g_{m1}\frac{1}{R}}{g_{m1} + g_{mb1} + \frac{1}{R}} R_L$$

$$\frac{v_o}{v_i} = -g_{m2}R_L \left(\frac{g_{m1} + \frac{g_{m1}}{g_{m2}R}}{g_{m1} + g_{mb1} + \frac{1}{R}} \right)$$

$$\frac{g_{mb1}}{g_{m1}} = \chi = \frac{\gamma}{2\sqrt{2\phi_F + V_{SB}}} = \frac{0.25}{2\sqrt{0.6 + 0.75}}$$

$$g_{m1} = \sqrt{2K' \frac{W}{L} I_D} = \sqrt{2(200)(4)(10)(0.75m)}$$

$$\frac{v_o}{v_i} = \frac{-0.25}{26} (1k) \frac{(1.73m) \left(1 + \frac{1}{\frac{0.25}{26} \cdot 912} \right)}{(1.73m)(1 + 0.108) + \frac{1}{912}}$$

$$= -9.6 (0.64) = -6.2$$

BICMOS DARLINGTON

```
VCC 100 0 3
RL 100 2 1K
M1 2 1 4 0 NMOS W=10U L=1U
VI 1 0 2.296
Q2 2 4 0 NPN
RB 4 0 1K
```

```
.MODEL NMOS NMOS LEVEL=1 VTO=0.6 KP=200U
```

```
+ LAMBDA=0 GAMMA=0.25 PHI=0.6
```

```
.MODEL NPN NPN IS=1E-16 BF=100 RB=0
```

```
.OPTIONS NOMOD NOPAGE
```

```
.WIDTH OUT=80
```

```
.TF V(2) VI
```

```
.DC VI 2.2 2.3 0.01
```

```
.PLOT DC V(2)
```

```
.OP
```

```
.END
```

```
***** DC TRANSFER CURVES THOM= 27.000 TEMP= 27.000
```

VOLT	V(2)	1.900E+00	2.000E+00	2.100E+00	2.200E+00	2.300E+00
2.200E+00	2.28E+00	+	+	+	+	+
2.210E+00	2.27E+00	+	+	+	+	+
2.220E+00	2.25E+00	+	+	+	+	+
2.230E+00	2.24E+00	+	+	+	+	+
2.240E+00	2.21E+00	+	+	+	+	+
2.250E+00	2.19E+00	+	+	+	+	+
2.260E+00	2.16E+00	+	+	+	+	+
2.270E+00	2.13E+00	+	+	+	+	+
2.280E+00	2.08E+00	+	+	+	+	+
2.290E+00	2.03E+00	+	+	+	+	+
2.300E+00	1.97E+00	+	+	+	+	+

```
**** OPERATING POINT INFORMATION THOM= 27 TEMP= 27
```

```
NODE =VOLTAGE NODE =VOLTAGE NODE =VOLTAGE
+0:1 = 2.296E+00 0:2 = 2.000E+00 0:4 = 7.391E-01
+0:100 = 3.000E+00
```

**** BIPOLAR JUNCTION TRANSISTORS

```
SUBCKT
ELEMENT 0:Q2
MODEL 0:NPN
IB 2.576E-06
IC 2.576E-04
VBE 7.391E-01
VCE 2.000E+00
VBC -1.261E+00
VS -2.000E+00
POWER 5.173E-04
BETAD 1.000E+02
GM 9.959E-03
RPI 1.004E+04
RI 0.
RO 1.261E+16
BETAC 9.999E+01
```

**** MOSFETS

```
SUBCKT
ELEMENT 0:M1
MODEL 0:NMOS
ID 7.417E-04
IBS -7.391E-15
IBD -2.001E-14
VGS 1.556E+00
VDS 1.261E+00
VBS -7.391E-01
VTH 6.957E-01
VDSAT 8.612E-01
BETA 2.000E-03
GAM EFF 2.500E-01
GM 1.722E-03
GDS 0.
GMB 1.861E-04
```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```
V(2)/VI = -6.332E+00
INPUT RESISTANCE AT VI = 1.000E+20
OUTPUT RESISTANCE AT V(2) = 9.999E+02
```

```

BICMOS DARLINGTON
* NONZERO LAMBDA, NONZERO BASE RESISTANCE, AND FINITE VA
VCC 100 0 3
RL 100 2 1K
M1 2 1 4 0 NMOS W=10U L=1U
VI 1 0 2.268
Q2 2 4 0 NPN
RB 4 0 1K
.MODEL NMOS NMOS LEVEL=1 VT0=0.6 KP=200U
+ LAMBDA=0.05 GAMMA=0.25 PHI=0.6
.MODEL NPN NPN IS=1E-16 BF=100 RB=100 VA=20
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF V(2) VI
.DC VI 2.2 2.3 0.01
.PLOT DC V(2)
.OP
.END

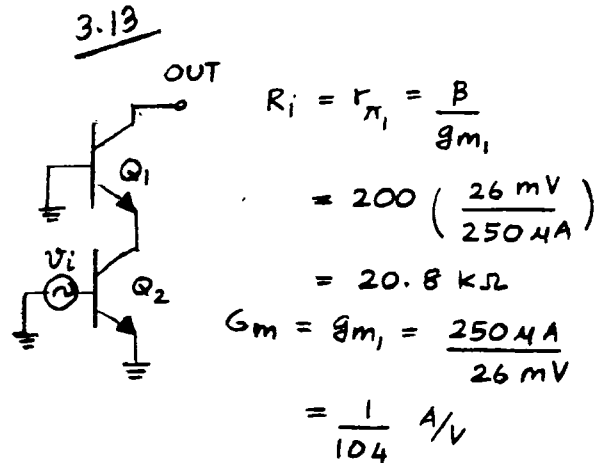
***** DC TRANSFER CURVES THOM= 27.000 TEMP= 27.000
VOLT V(2)
(A) 1.600E+00 1.800E+00 2.000E+00 2.200E+00 2.400E+00
+ + + + +
2.200E+00 2.23E+00 + + + + +A + +
2.210E+00 2.21E+00 + + + + +A + +
2.220E+00 2.18E+00 + + + + +A + +
2.230E+00 2.16E+00 + + + + +A + +
2.240E+00 2.12E+00 + + + + +A + +
2.250E+00 2.08E+00 + + + + +A + +
2.260E+00 2.04E+00 + + + + +A + +
2.270E+00 1.98E+00 + + + + +A + +
2.280E+00 1.92E+00 + + + + +A + +
2.290E+00 1.85E+00 + + + + +A + +
2.300E+00 1.77E+00 + + + + +A + +
+ + + + +
**** OPERATING POINT INFORMATION THOM= 27 TEMP= 27
NODE =VOLTAGE NODE =VOLTAGE NODE =VOLTAGE
+0:1 = 2.268E+00 0:2 = 2.000E+00 0:4 = 7.380E-01
+0:100 = 3.000E+00

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT 0:Q2
MODEL 0:NPN
IB 2.438E-06
IC 2.592E-04
VBE 7.380E-01
VCE 2.000E+00
VBC -1.262E+00
VS -2.000E+00
POWER 5.204E-04
BETAD 1.063E+02
GM 1.001E-02
RPI 1.060E+04
RX 1.000E+02
RO 8.202E+04
BETAAC 1.061E+02

**** MOSFETS
SUBCKT
ELEMENT 0:M1
MODEL 0:NMOS
ID 7.404E-04
IBS -7.380E-15
IBD -2.000E-14
VGS 1.530E+00
VDS 1.262E+00
VBS -7.380E-01
VTH 6.955E-01
VDSAT 8.345E-01
BETA 2.126E-03
GAM KFF 2.500E-01
GM 1.774E-03
GDS 3.482E-05
GMB 1.918E-04

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS
V(2)/VI = -5.557E+00
INPUT RESISTANCE AT VI = 1.000E+20
OUTPUT RESISTANCE AT V(2) = 8.802E+02

```



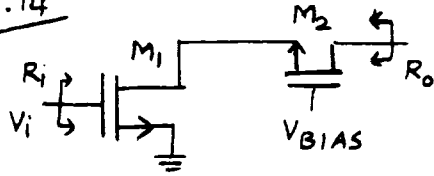
Using the results of 3.5, Q_1 is in effect a current source driving Q_2 ,

$$R_o = \beta r_{o2} = 200 \left(\frac{1}{\eta g_{m_1}} \right)$$

$$= 200 \left(\frac{26 \text{ mV}}{250 \mu\text{A}} \right) \left(\frac{1}{2 \times 10^{-4}} \right)$$

$$= 104 \text{ M}\Omega$$

3.14



$$R_i \rightarrow \infty$$

$$G_m = g_{m1} = \sqrt{2(90)(100)(250)}$$

$$\approx 2.1 \text{ mA/V}$$

$$R_o \approx (g_{m2} + g_{mb2}) r_{o2} r_{o1}$$

$$= g_{m2} (1 + \chi) r_{o2} r_{o1}$$

$$r_{o1} = r_{o2} = \frac{1}{\lambda I} = \frac{10}{250} = 40 \text{ k}\Omega$$

$$R_o \approx 2.1 (1 + 0.1) (40 \text{ k})^2 = 3.7 \text{ M}\Omega$$

3.15

From (3.133),

$$R_o \approx [g_{m2} (a+1) + g_{mb2}] r_{o1} r_{o2}$$

Ignore Body Effect,

$$R_o \approx g_{m2} (a+1) r_{o1} r_{o2}$$

From (1.163),

$$V_A = L_{\text{eff}} \left(\frac{d\chi_d}{dV_{DS}} \right)^{-1}$$

$$L_{\text{eff}} = L_{\text{drawn}} - 2L_d - \chi_d$$

$$= 0.4 - 2(0.09) - (0.1) = 0.12 \mu\text{m}$$

$$V_A = \frac{0.12}{0.02} = 6 \text{ V}$$

From (1.194),

$$r_{o1} = r_{o2} = r_{o3} = \frac{V_A}{I_D} = \frac{6 \text{ V}}{100 \mu\text{A}} = 60 \text{ k}\Omega$$

From (1.180)

$$g_{m1} = g_{m2} = g_3 = \sqrt{2\kappa' \frac{W}{L} I_D}$$

$$= 2 \sqrt{2(194) \left(\frac{10.4 \mu\text{m}}{0.124 \mu\text{m}} \right) (100)}$$

$$\approx 1800 \mu\text{A/V}$$

$$a = g_{m3} r_{o3} = 1.8 \frac{\text{mA}}{\text{V}} (60 \text{ k}\Omega)$$

$$= 108 = g_{m2} r_{o2}$$

$$R_o \approx (g_{m2} r_{o2}) (a+1) r_{o1}$$

$$= 108 (109) 60 \text{ k}\Omega$$

$$= 706 \text{ M}\Omega$$

SPICE gives $R_o = 1.15 \text{ G}\Omega$ for

$$V_o = 1.0 \text{ V}$$

The main difference between hand calculations and SPICE here stems from the fact that V_A is very small here.

As a result, V_{DS} is not negligible compared to V_A . So, $r_o = \frac{V_A + V_{DS}}{I_D}$

for each transistor

$$V_{DS1} = V_{GS3} \approx 0.7 \text{ V}$$

$$V_{DS2} = V_o - V_{DS1}$$

$$\text{If } V_o = 1.0 \text{ V, } V_{DS2} \approx 0.3 \text{ V}$$

$$V_{DS3} = V_{GS2} + V_{GS3} \approx 1.4 \text{ V}$$

$$r_{o1} = \frac{V_A + V_{DS1}}{I_{D1}} = \frac{6.7}{100 \mu\text{A}} = 67 \text{ k}\Omega$$

$$r_{o2} = \frac{6.3}{100 \mu\text{A}} = 63 \text{ k}\Omega$$

$$r_{o3} = \frac{7.4}{100 \mu\text{A}} = 74 \text{ k}\Omega$$

$$g_{m3} r_{o3} = 1.8 \frac{\text{mA}}{\text{V}} (74 \text{ k}) \approx 133$$

$$R_o = (1.8 \frac{\text{mA}}{\text{V}}) (63) (134) (67 \text{ k}) = 1.026 \text{ G}\Omega$$

ACTIVE CASCODE

VDD 100 0 3
I 100 3 100U
VI 10 0 0.7053
* THE INPUT VOLTAGE IS ADJUSTED BY TRIAL AND ERROR
* SO THAT ID1 = 100 UA.

VO 2 0 1
* THE OUTPUT VOLTAGE IS BIASED HIGH ENOUGH
* TO OPERATE M1 AND M2 IN THE ACTIVE REGION.

M1 1 10 0 0 CMOSN W=10U L=0.3U
M2 2 3 1 1 CMOSN W=10U L=0.3U
M3 3 1 0 0 CMOSN W=10U L=0.3U
* THE CHANNEL LENGTH IS ENTERED AS 0.3 MICRONS
* BECAUSE THE DRAWN LENGTH IS 0.4 MICRONS
* AND XD = 0.1 MICRONS
* NOTE THAT CONNECTING THE BODY TO THE SOURCE
* ELIMINATES THE BODY EFFECT.

.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0.1667 KP=194U
+ VTO=0.6 LD=0.09U
*LEFF = LDRON - 2LD - XD = 0.4 - 2(0.09) - 0.1 = 0.12U
*NOTE THAT LAMBDA = (DDX/DVDS)/LEFF = 0.02/0.12=0.1667

.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.TF V(2) VO
.END

**** OPERATING POINT INFORMATION TWCN= 27 TEMP= 27
NODE =VOLTAGE NODE =VOLTAGE NODE =VOLTAGE
+0:1 = 7.001E-01 0:2 = 1.000E+00 0:3 = 1.408E+00
+0:10 = 7.053E-01 0:100 = 3.000E+00

**** MOSFETS
SUBCKT
ELEMENT 0:M1 0:M2 0:M3
MODEL 0:CMOSN 0:CMOSN 0:CMOSN
ID 1.001E-04 1.001E-04 1.000E-04
IBS 0. 0. 0.
IRD -7.001E-15 -2.999E-15 -1.409E-14
VGS 7.053E-01 7.086E-01 7.001E-01
VDS 7.001E-01 2.999E-01 1.408E+00
VBS 0. 0. 0.
VTH 6.000E-01 6.000E-01 6.000E-01
VDSAT 1.053E-01 1.086E-01 1.001E-01
BETA 1.805E-02 1.697E-02 1.996E-02
GAM EFF 0. 0. 0.
GM 1.901E-03 1.843E-03 1.998E-03
GDS 1.494E-05 1.589E-05 1.350E-05
GMB 0. 0. 0.

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(2)/VO = 1.000E+00
INPUT RESISTANCE AT VO = 1.157E+09
OUTPUT RESISTANCE AT V(2) = 0.

3.16

From (3.7), $G_m = -\frac{a_v}{z_o}$

At low frequency, $z_o \approx R_o$

From (3.137), $R_o \approx \frac{1}{g_{m1} + g_{mb1}} \left(\frac{1}{g_{m2} r_{o1}} \right)$

From (3.141), $a_v \approx \frac{g_{m1}}{g_{m1} + g_{mb1}}$

$$\therefore G_m \approx -\frac{\frac{g_{m1}}{g_{m1} + g_{mb1}}}{\frac{1}{g_{m1} + g_{mb1}} \left(\frac{1}{g_{m2} r_{o1}} \right)} = -(g_{m1} r_{o1}) g_{m2}$$

From (1.163), $|V_{AP}| = L_{eff} \left(\frac{dx_d}{dV_{DS}} \right)^{-1}$

$$L_{eff} = L_{drawn} - 2L_d - X_d = 0.4 - 2(0.09) - 0.1 = 0.12 \mu m$$

$$|V_{AP}| = \frac{0.12}{0.04} = 3V$$

From (1.194), $r_{o1} = \frac{|V_{AP}|}{|I_{D1}|} = \frac{3V}{100 \mu A} = 30 k\Omega$

$$I_{D1} = -I_2 = -100 \mu A$$

From (1.180),

$$g_{m1} = \sqrt{2 K_p' \frac{W_1}{L_1} |I_{D1}|} = \sqrt{2 (65) \left(\frac{30}{0.12} \right) (100)} = 1800 \mu A/V$$

$$g_{m2} = \sqrt{2 K_n' \frac{W_2}{L_2} I_{D2}} = \sqrt{2 (194) \left(\frac{10}{0.12} \right) (100)} = 1800 \mu A/V$$

$$(I_{D2} = I_1 - I_2 = 100 \mu A)$$

$$\begin{aligned} G_m &= -\left(1800 \frac{\mu A}{V} \times 30 k\Omega \right) 1800 \frac{\mu A}{V} \\ &= -(54) \left(1800 \frac{\mu A}{V} \right) \\ &= -97.2 \frac{mA}{V} \end{aligned}$$

3.17

$$V_{CC} = I_{D2}(10K) + V_{BE2} + V_{GS2}$$

$$5 = I_{D2}(10K) + 0.7 + V_{GS2}$$

$$5 = \frac{200\mu}{2} \frac{20}{1} (V_{GS2} - 0.6)^2 (10K) + 0.7 + V_{GS2}$$

$$5 = 20(V_{GS2} - 0.6)^2 + 0.7 + V_{GS2}$$

$$0 = 20V_{GS2}^2 - 23V_{GS2} + 2.9$$

$$V_{GS2} = \frac{23 \pm \sqrt{(23)^2 - 4 \cdot 20 \cdot (2.9)}}{40}$$

$$= \frac{23 \pm 17.23}{40} = 1.006 \text{ or } 0.14$$

Too small for
 $I_{D2} > 0$

$$I_{D2} = \frac{200}{2} \frac{20}{1} (1.006 - 0.6)^2$$

$$= 330 \mu A$$

$$V_{BQ2} = 5 - I_{D2}(10K) = 1.7V$$

$$V_{EQ1} = 1.7 - 0.7 = 1.0V$$

$$I_{RL1} = \frac{5-1}{1K} = 4mA$$

$$I_{D1} = \frac{K'}{2} \left(\frac{W}{L} \right)_1 (V_{GS1} - V_t)^2 = I_{RL1} + I_{RL2}$$

Assume the dc input is adjusted so that $I_{C1} = I_{C2}$. Then,

$$V_{CQ1} = 5 - I_{C1}(10K) = 5 - 330\mu(10K)$$

$$= 1.7V$$

so, Q_1 operates in the forward active region,

$$I_{D1} = \frac{200}{2} \frac{300}{1} (V_{GS1} - 0.6)^2$$

$$= 4mA + 330\mu A = 4330\mu A = I_{D1}$$

$$V_{GS1} = 0.98V$$

small signal parameters:

$$g_m(M_1) = \sqrt{2(200) \frac{300}{1} (4330)}$$

$$= 22.8 \text{ mA/V}$$

$$g_m(M_2) = \sqrt{2(200) \frac{20}{1} (330)}$$

$$= 1.62 \frac{\text{mA}}{\text{V}} = \frac{1}{615\Omega}$$

$$g_m(Q_1) = \frac{330\mu A}{26\text{mV}} = \frac{1}{79\Omega} = g_m(Q_2)$$

$$I_{C3} = \frac{V_o}{1K} = \frac{V_c(Q_1) - V_{BE3}}{1K}$$

$$= \frac{1.7 - 0.7}{1K} = 1mA$$

$$g_m(Q_3) = \frac{1mA}{26\text{mV}} = \frac{1}{26\Omega}$$

$$r_{\pi}(Q_3) = \frac{\beta}{g_m(Q_3)} = \frac{100}{1/26} = 2.6K\Omega$$

M_1 converts changes in the input voltage to changes in the drain current of M_1 . The

conversion constant = $g_m(M_1)$

Let R_{i1} = resistance looking into the emitter of Q_1 .

$$R_{i1} = \frac{1}{g_m(Q_1)} + \frac{1/g_m(Q_2) + 1/g_m(M_2)}{\beta}$$

$$= 79 + \frac{79 + 615}{100} = 86\Omega$$

Use current divider to find the small signal current flowing from the emitter of Q_1

$$= -g_m(M_1) V_i \frac{R_{L1}}{R_{L1} + R_{i1}}$$

3-14

then the small-signal collector

$$\text{current of } Q_1 = -g_m(M_1) V_i \frac{R_{L1}}{R_{L1} + R_{i1}} \left(\frac{B}{B+1} \right)$$

The resistance to small-signal ground at the collector of Q_1

$$= R_{L2} \parallel (r_{\pi 3} + (B+1) R_{L3})$$

The gain of emitter follower Q_3

$$= \frac{g_m(Q_3) R_{L3}}{1 + g_m(Q_3) R_{L3}}$$

$$\begin{aligned} \frac{V_o}{V_i} &= -g_m(M_1) \frac{R_{L1}}{R_{L1} + R_{i1}} \left(\frac{B}{B+1} \right) \left\{ R_{L2} \parallel [r_{\pi 3} + (B+1) R_{L3}] \right\} \\ &\quad \times \frac{g_m(Q_3) R_{L3}}{1 + g_m(Q_3) R_{L3}} \\ &= -22.8 \frac{\text{mA}}{\text{V}} \left(\frac{1000}{1086} \right) \left(\frac{100}{101} \right) \left\{ 10 \text{ K} \parallel [2.6 \text{ K} + 101(1 \text{ K})] \right\} \left[\frac{1000/26}{1 + \frac{1000}{26}} \right] \\ &= -184 \end{aligned}$$

To model velocity saturation, use (1.232)

$$R_{SX1} = \frac{1}{\epsilon_c k' W_1} = \frac{1}{1.5 \times 10^6 (200 \mu\text{m})(300 \mu\text{m})} = 11.1 \Omega$$

$$R_{SX2} = \frac{1}{\epsilon_c k' W_2} = \frac{1}{1.5 \times 10^6 (200 \mu\text{m})(20 \mu\text{m})} = 167 \Omega$$

BICMOS AMPLIFIER (WITHOUT VELOCITY SATURATION)

VCC 100 0 5

* THE DC INPUT IS ADJUSTED BY TRIAL AND ERROR

*UNTIL THE DC OUTPUT IS ABOUT EQUAL TO THE DC INPUT.

VI 2 0 0.9793

M1 4 2 0 0 NMOS W=300U L=1U

Q1 3 5 4 NPN

Q2 5 5 6 NPN

RF 2 7 30K

RL1 100 4 1K

RL2 100 3 10K

RL3 7 0 1K

RBIAS 100 5 10K

Q3 100 3 7 NPN

M2 6 6 0 0 NMOS W=200U L=1U

.MODEL NMOS NMOS KP=200U LAMBDA=0 VTO=0.6

.MODEL NPN NPN IS=1E-16 BF=100 RB=0

.OPTIONS NOMOD NOPAGE

.WIDTH OUT=80

.OP

.TF V(7) VI

.END

**** OPERATING POINT INFORMATION TSW= 27 TEMP= 27

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:2	= 9.793E-01	0:3	= 1.756E+00	0:4	= 1.001E+00
+0:5	= 1.746E+00	0:6	= 1.001E+00	0:7	= 9.825E-01
+0:100	= 5.000E+00				

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT

ELEMENT	0:Q1	0:Q2	0:Q3
MODEL	0:NPN	0:NPN	0:NPN
IB	3.147E-06	3.191E-06	9.729E-06
IC	3.147E-04	3.191E-04	9.729E-04
VBE	7.443E-01	7.447E-01	7.735E-01
VCE	7.543E-01	7.447E-01	4.017E+00
VBC	-9.965E-03	0.	-3.244E+00
VS	-1.756E+00	-1.746E+00	-5.000E+00
POWER	2.397E-04	2.400E-04	3.916E-03
BETAD	1.000E+02	1.000E+02	1.000E+02
GM	1.217E-02	1.234E-02	3.762E-02
RPI	8.219E+03	8.106E+03	2.658E+03
RX	0.	0.	0.
RO	3.802E+14	2.586E+14	3.244E+16
BETAC	9.999E+01	9.999E+01	9.999E+01

**** MOSFETS

SUBCKT

ELEMENT	0:M1	0:M2
MODEL	0:NMOS	0:NMOS
ID	4.316E-03	3.222E-04
IBS	0.	0.
IBD	-1.002E-14	-1.001E-14
VGS	9.793E-01	1.001E+00
VDS	1.001E+00	1.001E+00
VBS	0.	0.
VTH	6.000E-01	6.000E-01
VDSAT	3.793E-01	4.014E-01
BETA	6.000E-02	4.000E-03
GAM EFF	0.	0.
GM	2.276E-02	1.606E-03
GDS	0.	0.
GMB	0.	0.

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(7)/VI	= -1.833E+02
INPUT RESISTANCE AT VI	= 1.627E+02
OUTPUT RESISTANCE AT V(7)	= 1.109E+02

BICMOS AMPLIFIER (WITH VELOCITY SATURATION MODEL)

```

*****
VCC 100 0 5
* THE DC INPUT IS ADJUSTED BY TRIAL AND ERROR
* UNTIL THE DC OUTPUT IS ABOUT EQUAL TO THE DC INPUT.
VI 2 0 1.0242
M1 4 2 11 0 NMOS W=300U L=1U
RSX1 11 0 11.1
Q1 3 5 4 NPN
Q2 5 5 6 NPN
RF 2 7 30K
RL1 100 4 1K
RL2 100 3 10K
RL3 7 0 1K
RBIAS 100 5 10K
Q3 100 3 7 NPN
M2 6 6 12 0 NMOS W=20U L=1U
RSX2 12 0 167
.MODEL NMOS NMOS KP=200U LAMBDA=0 VTO=0.6
.MODEL NPN NPN IS=1E-16 BF=100 RB=0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.TF V(7) VI
.END

```

```

**** OPERATING POINT INFORMATION THOM= 27 TEMP= 27
NODE =VOLTAGE NODE =VOLTAGE NODE =VOLTAGE
+0:2 = 1.024E+00 0:3 = 1.797E+00 0:4 = 1.051E+00
+0:5 = 1.795E+00 0:6 = 1.051E+00 0:7 = 1.023E+00
+0:11 = 4.730E-02 0:12 = 5.300E-02 0:100 = 5.000E+00

```

**** BIPOLAR JUNCTION TRANSISTORS

```

SUBCKT
ELEMENT 0:Q1 0:Q2 0:Q3
MODEL 0:NPN 0:NPN 0:NPN
IB 3.101E-06 3.142E-06 1.013E-05
IC 3.101E-04 3.142E-04 1.013E-03
VBE 7.439E-01 7.443E-01 7.745E-01
VCE 7.460E-01 7.443E-01 3.976E+00
VBC -2.051E-03 0. -3.202E+00
VS -1.797E+00 -1.795E+00 -5.000E+00
POWER 2.336E-04 2.362E-04 4.036E-03
BETAD 1.000E+02 1.000E+02 1.000E+02
GM 1.199E-02 1.215E-02 3.916E-02
RPI 8.340E+03 8.231E+03 2.553E+03
RX 0. 0. 0.
RO 2.799E+14 2.586E+14 3.202E+16
BETALC 9.999E+01 9.999E+01 9.999E+01

```

**** MOSFETS

```

SUBCKT
ELEMENT 0:M1 0:M2
MODEL 0:NMOS 0:NMOS
ID 4.262E-03 3.173E-04
IBS -4.730E-16 -5.300E-16
IBD -1.052E-14 -1.051E-14
VGS 9.769E-01 9.983E-01
VDS 1.004E+00 9.983E-01
VBS -4.730E-02 -5.300E-02
VTH 6.000E-01 6.000E-01
VDSAT 3.769E-01 3.983E-01
BETA 6.000E-02 4.000E-03
GAM KFF 0. 0.
GM 2.261E-02 1.593E-03
GDS 0. 0.
GMB 0. 0.

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(7)/VI = -1.454E+02
INPUT RESISTANCE AT VI = 2.048E+02
OUTPUT RESISTANCE AT V(7) = 1.101E+02

```

3.18

We first neglect the DC current through the 10 MΩ resistor.

$$A_{dm} = -g_m R_c = -\left(\frac{10.4 \mu A}{26 \text{ mV}}\right) 100 \text{ k}\Omega = -38$$

$$A_{cm} = \frac{-g_m R_c}{1 + 2g_m R_{TAIL} \left(1 + \frac{1}{\beta}\right)} = \frac{-38}{1 + 20 \times 10^6 \left(\frac{10.4 \mu A}{26 \text{ mV}}\right) \left(1 + \frac{1}{200}\right)} = -0.005$$

$$CMRR = \frac{A_{dm}}{A_{cm}} = 7.6 \times 10^3 = 78 \text{ dB}$$

$$R_{id} = 2r_{\pi} = 2 \times 200 \times \frac{26 \text{ mV}}{10.4 \mu A} = 2 \times 520 \text{ k}\Omega$$

$$= 1.04 \text{ M}\Omega$$

$$R_{ic} = r_{\pi} + 2 R_{TAIL} (1 + \beta)$$

$$= 520 \text{ k}\Omega + 2 \times 10^6 \times 201 = 402 \text{ M}\Omega$$

EMITTER-COUPLED PAIR (DIFFERENTIAL-MODE INPUT)

```

*****
VCC 100 0 5
VEE 200 0 -5
RC1 100 2 100K
RC2 100 5 100K
Q1 2 3 4 NPN
Q2 5 0 4 NPN
ITAIL 4 200 20U
RTAIL 4 200 10MEG
VI 3 0 0
.MODEL NPN NPN BF=200 RB=0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF V(2, 5) VI
.OP
.END
**** OPERATING POINT INFORMATION THOM= 27 TEMP= 27
NODE =VOLTAGE NODE =VOLTAGE NODE =VOLTAGE
+0:2 = 3.983E+00 0:3 = 0. 0:4 = -6.555E-01
+0:5 = 3.983E+00 0:100 = 5.000E+00 0:200 = -5.000E+00
**** SMALL-SIGNAL TRANSFER CHARACTERISTICS
V(2,5)/VI = -3.930E+01
INPUT RESISTANCE AT VI = 1.017E+06
OUTPUT RESISTANCE AT V(2,5) = 2.000E+05

```

EMITTER-COUPLED PAIR (COMMON-MODE INPUT)

```

*****
VCC 100 0 5
VEE 200 0 -5
RC1 100 2 100K
RC2 100 5 100K
Q1 2 3 4 NPN
Q2 5 13 4 NPN
ITAIL 4 200 20U
RTAIL 4 200 10MEG
VI 3 0 0
ECM 13 0 3 0 1

```



```
.MODEL NPN NPN BF=200 RB=0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF V(2) VI
.OP
.END
**** OPERATING POINT INFORMATION      THOM= 27 TEMP= 27
      NODE =VOLTAGE      NODE =VOLTAGE      NODE =VOLTAGE
+0:2   = 3.983E+00 0:3   = 0.      0:4   = -6.555E-01
+0:5   = 3.983E+00 0:13  = 0.      0:100  = 5.000E+00
+0:200 = -5.000E+00
**** SMALL-SIGNAL TRANSFER CHARACTERISTICS
V(2)/VI                               = -4.974E-03
INPUT RESISTANCE AT      VI           = 4.004E+09
OUTPUT RESISTANCE AT V(2)            = 9.999E+04
```

EMITTER-COUPLED PAIR (DIFFERENTIAL-MODE INPUT)
* WITH NONZERO RB AND FINITE VA

```
*****
VCC 100 0 5
VEE 200 0 -5
RC1 100 2 100K
RC2 100 5 100K
Q1 2 3 4 NPN
Q2 5 0 4 NPN
ITAIL 4 200 20U
RTAIL 4 200 10MEG
VI 3 0 0
.MODEL NPN NPN BF=200 RB=200 VA=130
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF V(2, 5) VI
.OP
.END
**** OPERATING POINT INFORMATION      THOM= 27 TEMP= 27
      NODE =VOLTAGE      NODE =VOLTAGE      NODE =VOLTAGE
+0:2   = 3.983E+00 0:3   = 0.      0:4   = -6.548E-01
+0:5   = 3.983E+00 0:100 = 5.000E+00 0:200 = -5.000E+00
**** SMALL-SIGNAL TRANSFER CHARACTERISTICS
V(2,5)/VI                             = -3.899E+01
INPUT RESISTANCE AT      VI            = 1.048E+06
OUTPUT RESISTANCE AT V(2,5)           = 1.984E+05
```

3.19

With 4 k Ω resistors (emitter degeneration)

$$A_{dm} = \frac{-g_m R_c}{1 + g_m R_E \left(1 + \frac{1}{\beta}\right)}$$

$$= \frac{-38}{1 + \left(\frac{10.4 \text{ A}}{26 \text{ mV}}\right) 4 \text{ K} \left(1 + \frac{1}{200}\right)}$$

$$= -14.9$$

$$A_{cm} = \frac{-g_m R_c}{1 + g_m (4 \text{ K} + 2 R_{TAIL}) \left(1 + \frac{1}{\beta}\right)}$$

$$\approx -0.005$$

$$CMRR = \frac{A_{dm}}{A_{cm}} = 2980 = 69 \text{ dB}$$

EMITTER-COUPLED PAIR WITH EMITTER DEGENERATION (DIFF MODE)

```
VCC 100 0 5
VEE 200 0 -5
RC1 100 2 100K
RC2 100 5 100K
RE1 14 4 4K
RE2 15 4 4K
Q1 2 3 14 NPN
Q2 5 0 15 NPN
ITAIL 4 200 20U
RTAIL 4 200 10MEG
VI 3 0 0
.MODEL NPN NPN BF=200 RB=0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF V(2, 5) VI
.END
```

```
**** OPERATING POINT INFORMATION      THOM= 27 TEMP= 27
      NODE =VOLTAGE      NODE =VOLTAGE      NODE =VOLTAGE
+0:2   = 3.983E+00 0:3   = 0.      0:4   = -6.964E-01
+0:5   = 3.983E+00 0:14  = -6.555E-01 0:15  = -6.555E-01
+0:100 = 5.000E+00 0:200 = -5.000E+00
**** SMALL-SIGNAL TRANSFER CHARACTERISTICS
V(2,5)/VI                             = -1.523E+01
INPUT RESISTANCE AT      VI            = 2.624E+06
OUTPUT RESISTANCE AT V(2,5)           = 2.000E+05
```

EMITTER-COUPLED PAIR WITH EMITTER DEGENERATION (COMMON MODE)

```
VCC 100 0 5
VEE 200 0 -5
RC1 100 2 100K
RC2 100 5 100K
RE1 14 4 4K
RE2 15 4 4K
Q1 2 3 14 NPN
Q2 5 13 15 NPN
ITAIL 4 200 20U
RTAIL 4 200 10MEG
VI 3 0 0
ECM 13 0 3 0 1
.MODEL NPN NPN BF=200 RB=0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF V(2) VI
.OP
.END
```

```
**** OPERATING POINT INFORMATION      THOM= 27 TEMP= 27
      NODE =VOLTAGE      NODE =VOLTAGE      NODE =VOLTAGE
+0:2   = 3.983E+00 0:3   = 0.      0:4   = -6.964E-01
+0:5   = 3.983E+00 0:13  = 0.      0:14  = -6.555E-01
+0:15  = -6.555E-01 0:100 = 5.000E+00 0:200 = -5.000E+00
**** SMALL-SIGNAL TRANSFER CHARACTERISTICS
V(2)/VI                               = -4.973E-03
INPUT RESISTANCE AT      VI            = 4.005E+09
OUTPUT RESISTANCE AT V(2)            = 9.999E+04
```

EMITTER-COUPLED PAIR WITH EMITTER DEGENERATION (DIFF MODE)
* WITH NONZERO RB AND FINITE VA

```
VCC 100 0 5
VEE 200 0 -5
RC1 100 2 100K
RC2 100 5 100K
RE1 14 4 4K
RE2 15 4 4K
Q1 2 3 14 NPN
Q2 5 0 15 NPN
ITAIL 4 200 20U
RTAIL 4 200 10MEG
VI 3 0 0
.MODEL NPN NPN BF=200 RB=200 VA=130
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF V(2, 5) VI
.OP
.END
```

```
**** OPERATING POINT INFORMATION      THOM= 27 TEMP= 27
      NODE =VOLTAGE      NODE =VOLTAGE      NODE =VOLTAGE
+0:2   = 3.983E+00 0:3   = 0.      0:4   = -6.956E-01
+0:5   = 3.983E+00 0:14  = -6.548E-01 0:15  = -6.548E-01
+0:100 = 5.000E+00 0:200 = -5.000E+00
**** SMALL-SIGNAL TRANSFER CHARACTERISTICS
V(2,5)/VI                             = -1.518E+01
INPUT RESISTANCE AT      VI            = 2.690E+06
OUTPUT RESISTANCE AT V(2,5)           = 1.994E+05
```

3.20

First consider the balanced case in which the $10\text{ k}\Omega$ resistor is present in the collector of Q_1 .

For this,

$$I_{C1} = I_{C2} = \frac{1}{2} \left(\frac{15\text{ V} - 0.7\text{ V}}{10\text{ k}\Omega} \right) = 0.71\text{ mA}$$

$$A_{dm} = -g_m R_C = -10\text{ k} \left(\frac{0.71\text{ mA}}{26\text{ mV}} \right) = -273$$

$$A_{cm} = \frac{-g_m R_C}{1 + 2g_m R_E \left(1 + \frac{1}{\beta}\right)} \approx \frac{-R_C}{2R_{TAIL}} = -\frac{1}{2}$$

Now, we are applying a signal to the V_{i1} input, and taking the V_{o2} output only.

$$V_{o2} = V_{oc} - \frac{V_{od}}{2} = A_{cm} V_{ic} - \frac{1}{2} A_{dm} V_{id}$$

$$\text{Now, } V_{ic} = \frac{V_{i1} + V_{i2}}{2} = \frac{1}{2} V_i$$

$$V_{id} = V_{i1} - V_{i2} = V_i$$

$$\text{Thus, } V_{o2} = A_{cm} \left(\frac{1}{2} V_i \right) - \frac{1}{2} A_{dm} V_i$$

$$\frac{V_{o2}}{V_i} = \frac{1}{2} (A_{cm} - A_{dm}) = \frac{1}{2} \left(-\frac{1}{2} - (-273) \right) = 136$$

The common mode input resistance is much larger than the D.M. input resistance, so

$$R_i \approx R_{id} = 2r_{\pi} = 2\beta \left(\frac{26\text{ mV}}{0.71\text{ mA}} \right)$$

$$\therefore R_i = 14.6\text{ k}\Omega$$

By inspection, if we neglect r_o ,

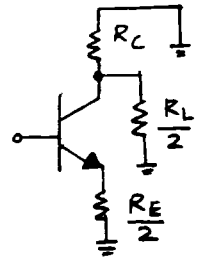
$$R_{out} = R_C = 10\text{ k}\Omega$$

3.21

The D.M. Half circuit is :

$$R_{Ceff} = R_C \parallel \frac{R_L}{2}$$

$$R_{Eeff} = \frac{R_E}{2}$$

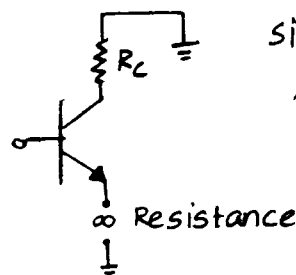


$$A_{dm} = \frac{g_m R_{Ceff}}{1 + g_m R_{Eeff} \left(1 + \frac{1}{\beta}\right)} = \frac{g_m (R_C \parallel \frac{R_L}{2})}{1 + g_m \frac{R_E}{2} \left(1 + \frac{1}{\beta}\right)}$$

Similarly,

$$R_{id} = 2 \left[r_{\pi} + (1 + \beta) \frac{R_E}{2} \right]$$

The C.M. half-circuit looks like:

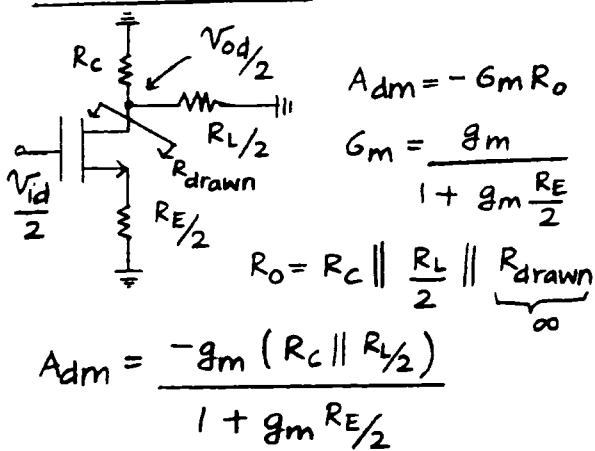
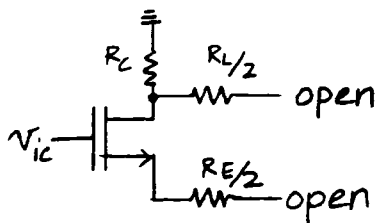


Since $R_E = \infty$

$$A_{cm} = 0$$

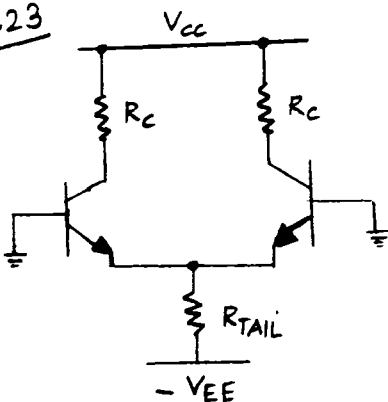
$$R_{ic} = \infty$$

3.22

D.M. $\frac{1}{2}$ circuit :C.M. $\frac{1}{2}$ circuit :

Since the resistance connected to the source $\rightarrow \infty$, G_m here = 0 and $A_{cm} = 0$

3.23



For, $R_{id} = 2 M\Omega$, $r_{\pi} = 1 M\Omega = \frac{\beta}{g_m}$

$$\therefore g_m = \frac{\beta}{10^6 \Omega} = \frac{200}{10^6 \Omega} = \frac{1}{5 k\Omega}$$

$$\therefore I_C = V_T / 5 k\Omega = 5.2 \mu A$$

$$\text{Now, } A_{dm} = -g_m R_C = -500$$

$$\therefore R_C = 500 / \frac{1}{5 k\Omega} = 2.5 M\Omega$$

The DC voltage drop across R_C is $I_C R_C = (5.2 \times 10^{-6}) (2.5 \times 10^6) = 13 V$

For a transistor V_{CE} of 1 V, when the bases are grounded,

$$V_{CB} = V_{CE} - V_{BE} = 0.3 V$$

$$\therefore V_{CC} = 0.3 V + 13 V = 13.3 V$$

$$A_{cm} \approx -\frac{R_C}{2 R_{TAIL}} ; A_{dm} = -g_m R_C$$

$$CMRR = \frac{A_{dm}}{A_{cm}} = \frac{-g_m R_C}{-R_C / 2 R_{TAIL}} = 2 g_m R_{TAIL}$$

$$\text{For } CMRR = 500, 2 g_m R_{TAIL} = 500$$

$$R_{TAIL} = \frac{500}{2 (\frac{1}{5 k})} = 1.25 M\Omega$$

since $I_{C1} + I_{C2} = 10.4 \mu A$, the voltage drop in R_{TAIL} is :

$$(I_{C1} + I_{C2}) R_{TAIL} = 10.4 \times 1.25 = 13 V$$

$$\text{and } V_{EE} = 13 + V_{BE} = 13.7 V$$

3.24

From Table (2.4),

$$\mu_n C_{ox} = 450 \times \frac{3.9 \times 8.854 \times 10^{-14}}{0.08 \times 10^{-5}}$$

$$= 194 \mu A/V^2 = K'$$

$$\Delta I_d = 0.85 I_{TAIL}$$

$$= \frac{K'}{2} \frac{W}{L_{eff}} (0.2) \sqrt{\frac{2 I_{TAIL}}{\frac{K'}{2} \frac{W}{L_{eff}}} - (0.2)^2} \quad \text{--- (1)}$$

$$\text{Also, } G_m = 1.0 \frac{mA}{V} = \sqrt{I_{TAIL} K' \frac{W}{L_{eff}}}$$

$$\Rightarrow K' \frac{W}{L_{eff}} = \frac{1 \times 10^{-6} A/V^2}{I_{TAIL}} \quad \text{--- (2)}$$

Substituting (2) in (1),

$$0.85 I_{TAIL} = \frac{1 \times 10^{-6} (0.2)}{2 I_{TAIL}} \sqrt{\frac{2 I_{TAIL}}{\frac{K'}{2} \frac{W}{L_{eff}}} - (0.2)^2}$$

Solve for I_{TAIL}^2 :

$$7.225 \times 10^{13} I_{TAIL}^4 - 4 \times 10^6 I_{TAIL}^2 + 0.04 = 0$$

$$I_{TAIL}^2 = \frac{4 \times 10^6 \pm \sqrt{(4 \times 10^6)^2 - 4 (7.225 \times 10^{13}) (0.04)}}{2 (7.225 \times 10^{13})}$$

$$= 2.768 \times 10^{-8} \pm 1.458 \times 10^{-8}$$

$$I_{TAIL}^2 = 4.226 \times 10^{-8} \text{ or } 1.310 \times 10^{-8}$$

$$I_{TAIL} = 205.6 \mu A \text{ or } 114.4 \mu A$$

If $I_{TAIL} = 205.6 \mu A$,

$$\frac{W}{L_{eff}} = \frac{1 \times 10^{-6}}{194 \times 10^{-6} (205.6 \times 10^{-6})} = 25.1$$

$$V_{OV} = \sqrt{\frac{205.6}{194 (25)}} = 0.206 V$$

If $I_{TAIL} = 114.4 \mu A$,

$$\frac{W}{L_{eff}} = \frac{1 \times 10^{-6}}{194 \times 10^{-6} (114.4 \times 10^{-6})} = 45.0$$

$$V_{OV} = \sqrt{\frac{114.4}{194 (45)}} = 0.114 V$$

This overdrive is too small because the range would be only $\pm \sqrt{2} (0.14)$ which is 162 mV which is less than the 200 mV input.

$$L_{eff} = L_{drawn} - 2L_d - X_d = 1 \mu m - 2(0.09) - 0$$

$$= 0.82 \mu m$$

$$\Rightarrow \frac{W}{L_{eff}} = \frac{W}{0.82 \mu m} = 25.1$$

$$\Rightarrow W = 20.6 \mu m ; I_{TAIL} = 205.6 \mu A$$

3.25

For the emitter coupled pair, using (3.216),

$$|V_{os}| = V_T \left(\frac{\Delta I_s}{I_s} + \frac{\Delta R_c}{R_c} \right)$$

But, for uniform-base transistor,

$$\left| \frac{\Delta I_s}{I_s} \right| = \left| \frac{\Delta W_B}{W_B} \right|$$

Thus, in this case,

$$|V_{os}| = V_T \left(\frac{\Delta W_B}{W_B} \right) = 26 mV \times 0.1$$

$$= 2.6 mV$$

3.26

From (3.248),

$$V_{os} = \Delta V_t + \frac{(V_{GS} - V_t)}{2} \left(-\frac{\Delta R_L}{R_L} - \frac{\Delta(W/L)}{W/L} \right)$$

$$V_{GS} - V_t = \sqrt{\frac{I_{TAIL}}{K' W/L_{eff}}}$$

$$K' = \frac{450 \times 3.39 \times 8.86 \times 10^{14}}{80 \times 10^{-8}} = 194 \mu A/V^2$$

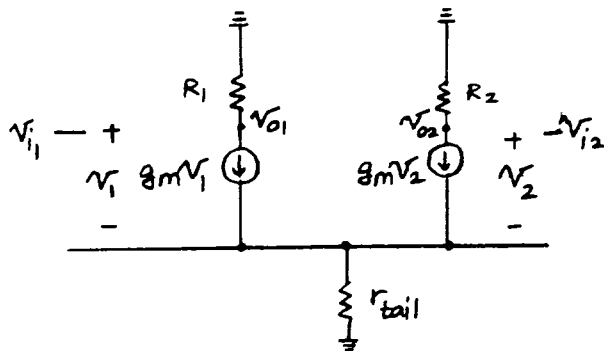
$$L_{eff} = 1 - 2(0.09) = 0.82 \mu m$$

$$V_{GS} - V_t = \sqrt{\frac{50 \mu A}{194 \mu \left(\frac{10}{0.82} \right)}} = 0.145$$

If $(W/L)_1 > (W/L)_2$, $V_{os} < 0$ since we don't know whether $(W/L)_1 > (W/L)_2$ or $(W/L)_2 > (W/L)_1$, we can only calculatethe magnitude of V_{os}

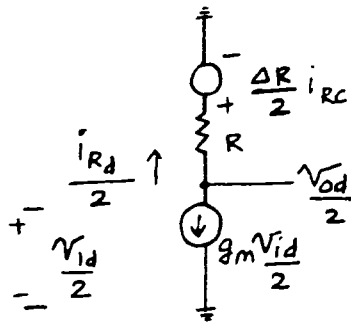
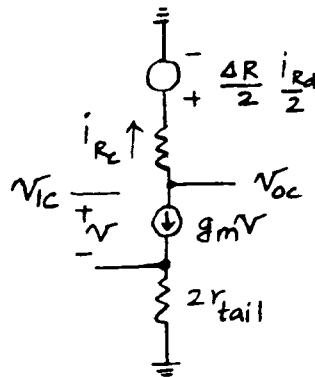
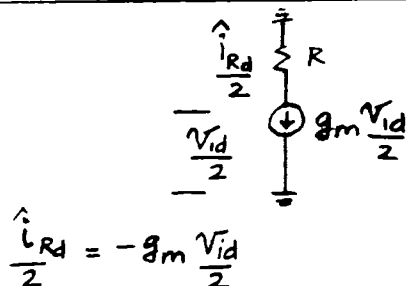
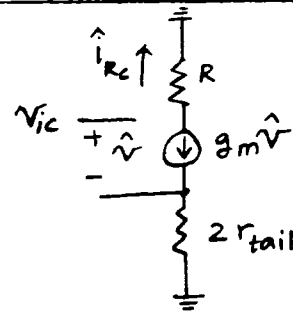
$$|V_{os}| = 0 + \frac{0.145}{2} (0 + 0.02) = 1.45 \text{ mV}$$

3.27



$$\text{Let } R = \frac{R_1 + R_2}{2}$$

$$\Delta R = R_1 - R_2$$

Exact D.M. $\frac{1}{2}$ circuit:Exact C.M. $\frac{1}{2}$ circuit:D.M. $\frac{1}{2}$ circuit without mismatch:C.M. $\frac{1}{2}$ circuit without mismatch:

$$\hat{i}_{Rc} = \frac{-g_m V_{ic}}{1 + 2g_m r_{tail}}$$

From exact $\frac{1}{2}$ circuits ;

$$V_{od} = \frac{\Delta R}{2} i_{Rc} + R \frac{i_{Rd}}{2} \approx \frac{\Delta R}{2} \hat{i}_{Rc} + R \frac{\hat{i}_{Rd}}{2}$$

$$= -\frac{\Delta R}{2} \frac{g_m V_{ic}}{1 + 2g_m r_{tail}} - R \frac{g_m V_{id}}{2}$$

$$\therefore A_{dm} \approx -g_m R = -1(10) = -10$$

$$A_{cm-dm} \approx \frac{-g_m \Delta R}{1 + 2g_m r_{tail}} = \frac{-1(0.2)}{1 + 2(1)(1000)} = -1 \times 10^{-4}$$

$$V_{oc} = \frac{\Delta R}{2} \frac{i_{Rd}}{2} + R i_{Rc} \approx \frac{\Delta R}{2} \frac{\hat{i}_{Rd}}{2} + R \hat{i}_{Rc}$$

$$= -\frac{\Delta R}{2} \frac{g_m V_{id}}{2} - R \frac{g_m V_{ic}}{1 + 2g_m r_{tail}}$$

$$\therefore A_{dm-cm} \approx \frac{-g_m \Delta R}{4} = \frac{-1(0.2)}{4} = -0.05$$

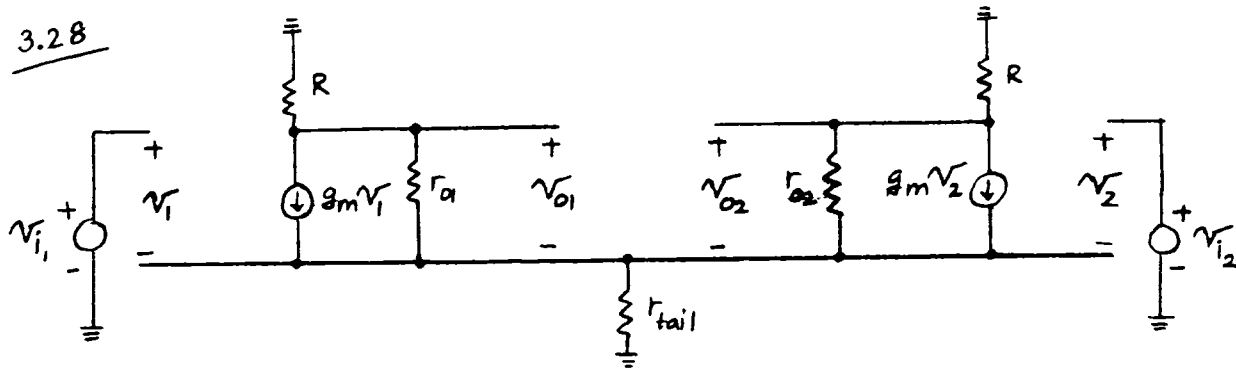
$$A_{cm} = \frac{-g_m R}{1 + 2g_m r_{tail}} = \frac{-1(10)}{1 + 2(1)(1000)} \approx -0.005$$

$$\frac{A_{dm}}{A_{cm}} \approx \frac{10}{0.005} = 2000$$

$$\frac{A_{dm}}{A_{cm-dm}} \approx \frac{10}{1 \times 10^{-4}} = 100,000$$

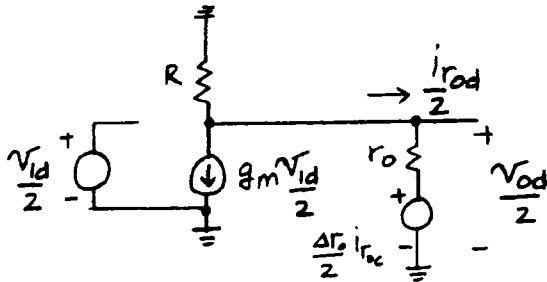
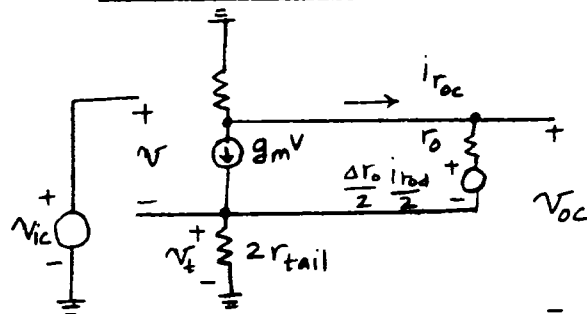
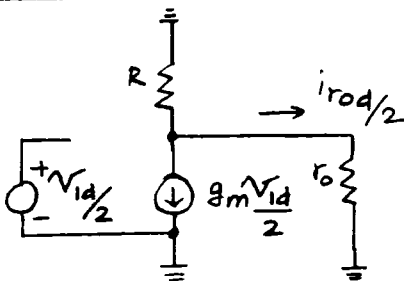
$$\frac{A_{dm}}{A_{dm-cm}} \approx \frac{10}{0.05} = 200$$

3.28

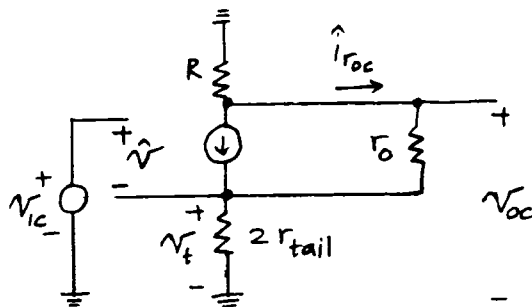


$$\text{Let } r_o = \frac{r_{o1} + r_{o2}}{2}$$

$$\Delta r_o = r_{o1} - r_{o2}$$

Exact D.M. $\frac{1}{2}$ circuit:Exact C.M. $\frac{1}{2}$ circuit:D.M. $\frac{1}{2}$ circuit without mismatch:

$$\hat{i}_{rod} = -gm \frac{V_{id}}{2} \left(\frac{R}{R + r_o} \right)$$

C.M. $\frac{1}{2}$ circuit without mismatch:

The bottom of the CM $\frac{1}{2}$ circuit is essentially a source follower, since $gm(2r_{tail}) \gg 1$, $V_t \approx V_{ic}$. Also, the current that flows in R is equal to the current

that flows in $2r_{tail}$. So,

$$\frac{-V_{oc}}{R} = \frac{V_t}{2r_{tail}}$$

$$\begin{aligned} \hat{i}_{roc} &= \frac{V_{oc} - V_t}{r_o} = \frac{-V_t \left(\frac{R}{2r_{tail}} + 1 \right)}{r_o} \\ &\approx -V_t / r_o \approx -V_{ic} / r_o \end{aligned}$$

From exact D.M. $\frac{1}{2}$ circuit,

$$\begin{aligned}\frac{V_{od}}{2} &= \frac{\Delta r_o}{2} i_{roc} \frac{R}{R+r_o} + \frac{i_{rod}}{2} r_o \\ &\approx \frac{\Delta r_o}{2} \hat{i}_{roc} \frac{R}{R+r_o} + \frac{\hat{i}_{rod}}{2} r_o \\ &\approx \frac{\Delta r_o}{2} \left(-\frac{V_{ic}}{r_o} \right) \frac{R}{R+r_o} - g_m \frac{V_{id}}{2} \frac{R}{R+r_o} r_o\end{aligned}$$

$$\begin{aligned}A_{dm} &= \frac{V_{od}}{V_{id}} = -g_m r_o \frac{R}{R+r_o} = 1m(500k) \left(\frac{10}{510} \right) \\ &= -9.8\end{aligned}$$

$$\begin{aligned}A_{cm-dm} &= \frac{V_{od}}{V_{ic}} = -\frac{\Delta r_o}{r_o} \frac{R}{R+r_o} = \frac{-10k}{500k} \frac{10}{510} \\ &= -3.9 \times 10^{-4}\end{aligned}$$

From exact C.M. $\frac{1}{2}$ circuit,

Use superposition,

First, set $i_{rod} = 0$,

$$V_{oc} = \frac{-R}{2r_{tail}} V_t = \frac{-R}{2r_{tail}} V_{ic}$$

$$A_{cm} = \frac{V_{oc}}{V_{ic}} \approx \frac{-R}{2r_{tail}} = \frac{-10}{2000} = -0.005$$

second, set $V_{ic} = 0$,

From KCL (with $V = 0 - V_t$)

$$g_m V_t + \frac{V_t}{2r_{tail}} + \frac{V_t + \frac{\Delta r_o}{2} \frac{i_{rod}}{2} - V_{oc}}{r_o} = 0$$

$$V_t \left(g_m + \frac{1}{2r_{tail}} + \frac{1}{r_o} \right) + \frac{\Delta r_o}{r_o} \frac{i_{rod}}{4} - \frac{V_{oc}}{r_o} = 0$$

$\approx g_m$

$$\text{Also, } V_t = -\frac{2r_{tail}}{R} V_{oc}$$

$$\frac{\Delta r_o}{r_o} \frac{i_{rod}}{4} = \frac{V_{oc}}{r_o} + \frac{2r_{tail}}{R} g_m V_{oc}$$

$$\text{Use } i_{rod} \approx \hat{i}_{rod} = -g_m V_{id} \frac{R}{R+r_o}$$

$$\begin{aligned}\frac{\Delta r_o}{r_o} \left(-g_m \frac{V_{id}}{4} \frac{R}{R+r_o} \right) &= V_{oc} \left(\frac{1}{r_o} + \frac{2r_{tail}}{R} g_m \right) \\ &\approx V_{oc} \frac{2r_{tail}}{R} g_m\end{aligned}$$

$$\begin{aligned}A_{dm-cm} &= \frac{V_{oc}}{V_{id}} \approx -\frac{1}{4} \frac{\Delta r_o}{r_o} \frac{R}{R+r_o} \frac{R}{2r_{tail}} \\ &= -\frac{1}{4} \frac{10}{500} \frac{10}{510} \frac{10}{2000} \\ &= -4.9 \times 10^{-7}\end{aligned}$$

As $r_{tail} \rightarrow \infty$

$$A_{dm} = -g_m r_o \left(\frac{R}{R+r_o} \right) = -9.8$$

$$A_{cm-dm} = -\frac{\Delta r_o}{r_o} \frac{R}{R+r_o} = -3.9 \times 10^{-4}$$

Both of these values are unchanged from the case with finite r_{tail}

$$A_{cm} \approx \frac{-R}{2r_{tail}} = 0 \text{ as } r_{tail} \rightarrow \infty$$

$$\begin{aligned}A_{dm-cm} &\approx -\frac{1}{4} \frac{\Delta r_o}{r_o} \frac{R}{R+r_o} \frac{R}{2r_{tail}} \\ &= 0 \text{ as } r_{tail} \rightarrow \infty\end{aligned}$$

CHAPTER 4

4.1

Assume

(1) All transistors are identical

$$I_{S1} = I_{S2} = I_{S3} = I_{S4} = I_{S5} = I_S$$

(2) $V_{BE(on)} = 0.7 \text{ V}$

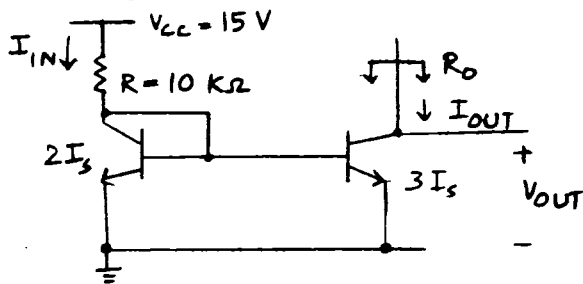
(3) $V_A = 130 \text{ V}$

(4) $\beta_F \rightarrow \infty$ (to ignore base currents)

transistors Q_1 and Q_2 operate in parallel and can be replaced by one equivalent transistor Q_A with a saturation current of $2I_S$

Similarly, transistors Q_3 - Q_5 operate in parallel and can be replaced by one equivalent transistor Q_B with a saturation current of $3I_S$.

Redrawing the circuit,



From (4.8) with $\beta_F \rightarrow \infty$

$$I_{OUT} = \frac{I_{SB}}{I_{SA}} I_N \left(1 + \frac{V_{CEB} - V_{CEA}}{V_A} \right)$$

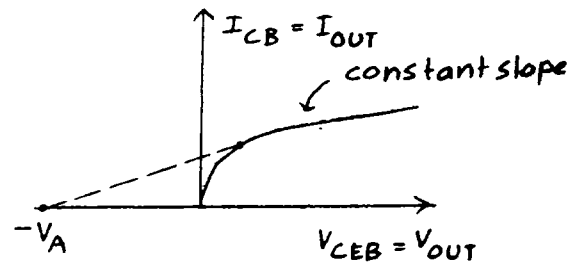
$$I_{IN} = \frac{15 - 0.7}{10 \text{ k}} = 1.43 \text{ mA}$$

$$I_{OUT} = \frac{3I_S}{2I_S} (1.43 \text{ mA}) \left(1 + \frac{V_{OUT} - 0.7}{130} \right)$$

$$I_{OUT}(V_{OUT} = 1 \text{ V}) = \frac{3}{2} (1.43) \left(1 + \frac{0.3}{130} \right) = 2.15 \text{ mA}$$

$$I_{OUT}(V_{OUT} = 5 \text{ V}) = \frac{3}{2} (1.43) \left(1 + \frac{4.3}{130} \right) = 2.22 \text{ mA}$$

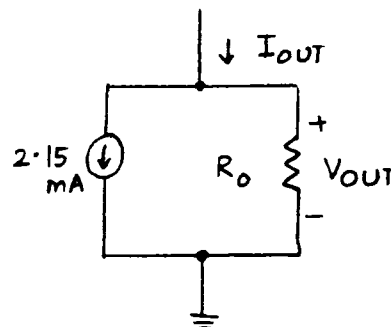
$$I_{OUT}(V_{OUT} = 30 \text{ V}) = \frac{3}{2} (1.43) \left(1 + \frac{29.3}{130} \right) = 2.63 \text{ mA}$$



$$R_O = r_{oB} = \frac{1}{\text{slope}} = \frac{V_A + V_{CEB}}{I_{CB}}$$

$$\approx \frac{V_A}{I_{OUT}(V_{OUT} = 1 \text{ V})} = \frac{130}{2.15 \text{ mA}} = 60.5 \text{ k}\Omega$$

We can model the output of the current mirror as,



SIMPLE CURRENT MIRROR SIMULATION (IGNORE BASE CURRENTS)

```

VCC 100 0 15
R 100 1 10K
Q1 1 1 0 NPN
Q2 1 1 0 NPN
Q3 2 1 0 NPN
Q4 2 1 0 NPN
Q5 2 1 0 NPN
VO 2 0 1
.MODEL NPN NPN BF=10000 VAF=130
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VO 1 30 1
.PLOT I(VO)
.TF V(2) VO
.END

```

***** DC TRANSFER CURVES TNOM= 27.000 TEMP= 27.000

VCLT	I(VC)				
(A)		-2.800E-03	-2.600E-03	-2.400E-03	-2.200E-03
1.000E+00	-2.14E-03	+	+	+	+
2.000E+00	-2.15E-03	+	+	+	+
3.000E+00	-2.17E-03	+	+	+	+
4.000E+00	-2.29E-03	+	+	+	+
5.000E+00	-2.20E-03	+	+	+	+
6.000E+00	-2.22E-03	+	+	+	+
7.000E+00	-2.24E-03	+	+	+	+
8.000E+00	-2.25E-03	+	+	+	+
9.000E+00	-2.27E-03	+	+	+	+
1.000E+01	-2.29E-03	+	+	+	+
1.100E+01	-2.30E-03	+	+	+	+
1.200E+01	-2.32E-03	+	+	+	+
1.300E+01	-2.34E-03	+	+	+	+
1.400E+01	-2.35E-03	+	+	+	+
1.500E+01	-2.37E-03	+	+	+	+
1.600E+01	-2.38E-03	+	+	+	+
1.700E+01	-2.40E-03	+	+	+	+
1.800E+01	-2.42E-03	+	+	+	+
1.900E+01	-2.43E-03	+	+	+	+
2.000E+01	-2.45E-03	+	+	+	+
2.100E+01	-2.47E-03	+	+	+	+
2.200E+01	-2.48E-03	+	+	+	+
2.300E+01	-2.50E-03	+	+	+	+
2.400E+01	-2.52E-03	+	+	+	+
2.500E+01	-2.53E-03	+	+	+	+
2.600E+01	-2.55E-03	+	+	+	+
2.700E+01	-2.57E-03	+	+	+	+
2.800E+01	-2.58E-03	+	+	+	+
2.900E+01	-2.60E-03	+	+	+	+
3.000E+01	-2.61E-03	+	+	+	+

```

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000
NODE =VOLTAGE NODE =VOLTAGE NODE =VOLTAGE
+0:1 = 7.654E-01 0:2 = 1.000E+00 0:100 = 1.500E+01

```

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT

ELEMENT	0:Q1	0:Q2	0:Q3	0:Q4	0:Q5
MODEL	0:NPN	0:NPN	0:NPN	0:NPN	0:NPN
IB	7.116E-08	7.116E-08	7.116E-08	7.116E-08	7.116E-08
IC	7.116E-04	7.116E-04	7.128E-04	7.128E-04	7.128E-04
VBE	7.654E-01	7.654E-01	7.654E-01	7.654E-01	7.654E-01
VCE	7.654E-01	7.654E-01	1.000E+00	1.000E+00	1.000E+00
VBC	0.	0.	-2.346E-01	-2.346E-01	-2.346E-01
VS	-7.654E-01	-7.654E-01	-1.000E+00	-1.000E+00	-1.000E+00
POWER	5.447E-04	5.447E-04	7.129E-04	7.129E-04	7.129E-04
BETAD	9.999E+03	9.999E+03	1.001E+04	1.001E+04	1.001E+04
GM	2.751E-02	2.751E-02	2.756E-02	2.756E-02	2.756E-02
RPI	3.634E+05	3.634E+05	3.634E+05	3.634E+05	3.634E+05
RX	0.	0.	0.	0.	0.
RO	1.827E+05	1.827E+05	1.827E+05	1.827E+05	1.827E+05
BETAC	9.998E+03	9.998E+03	1.001E+04	1.001E+04	1.001E+04

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(2)/VO = 1.000E+00
INPUT RESISTANCE AT VO = 6.090E+04

```

4.2

Assume

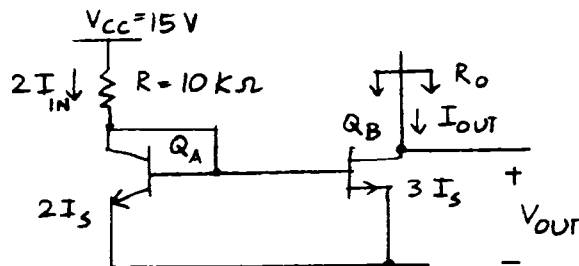
(1) All transistors are identical

$$I_{S1} = I_{S2} = I_{S3} = I_{S4} = I_{S5} = I_S$$

(2) $V_{BE(on)} = 0.7V$ (3) $V_A = 130V$ (4) $\beta_F = 200$

Transistors Q_1 and Q_2 operate in parallel and can be replaced by an equivalent transistor with a saturation current of $2I_S$ similarly, transistors Q_3 - Q_5 operate in parallel and can be replaced by an equivalent transistor Q_B with a saturation current of $3I_S$

Redrawing the circuit.



$$I_{IN} = \frac{15 - 0.7}{10K} = 1.43 \text{ mA}$$

From (4.8),

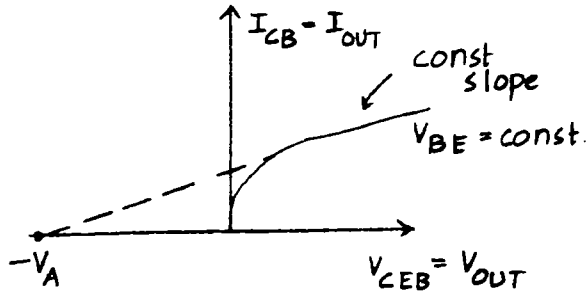
$$I_{OUT} = \frac{\frac{I_{SB}}{I_{SA}} I_{IN} \left(1 + \frac{V_{CEB} - V_{CEA}}{V_A}\right)}{1 + \frac{1 + I_{SB}/I_{SA}}{\beta_F}}$$

$$I_{OUT} = \frac{\frac{3}{2} (1.43 \text{ mA}) \left(1 + \frac{V_{OUT} - 0.7}{130}\right)}{1 + \frac{1 + 3/2}{200}}$$

$$I_{OUT}(V_{OUT}=1V) = 2.12 \text{ mA}$$

$$I_{OUT}(V_{OUT}=5V) = 2.19 \text{ mA}$$

$$I_{OUT}(V_{OUT}=30V) = 2.60 \text{ mA}$$

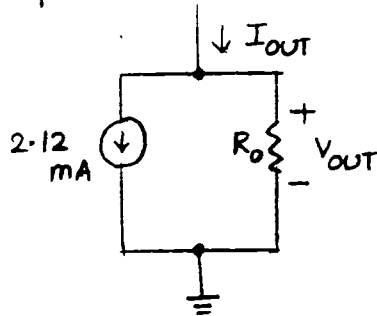


$$R_O = r_{OB} = 1/\text{slope}$$

$$= \frac{V_A + V_{CEB}}{I_C} \approx \frac{V_A}{I_{OUT}}$$

$$\approx \frac{130}{2.12 \text{ mA}} = 61.3 \text{ k}\Omega$$

output model:



SIMPLE CURRENT MIRROR SIMULATION (INCLUDE BASE CURRENTS)

```
*****
VCC 100 0 15
R 100 1 10K
Q1 1 1 0 NPN
Q2 1 1 0 NPN
Q3 2 1 0 NPN
Q4 2 1 0 NPN
Q5 2 1 0 NPN
VO 2 0 1
.MODEL NPN NPN BF=200 VAF=130
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VO 1 30 1
.PLOT I(VO)
.TF V(2) VO
.END
```

***** DC TRANSFER CURVES TNOM= 27.000 TEMP= 27.000

VOLT	I(VO)				
(A)		-2.600E-03	-2.400E-03	-2.200E-03	-2.000E-03
1.000E+00	-2.11E-03				
2.000E+00	-2.13E-03				
3.000E+00	-2.15E-03				
4.000E+00	-2.16E-03				
5.000E+00	-2.18E-03				
6.000E+00	-2.19E-03				
7.000E+00	-2.21E-03				
8.000E+00	-2.23E-03				
9.000E+00	-2.24E-03				
1.000E+01	-2.26E-03				
1.100E+01	-2.27E-03				
1.200E+01	-2.29E-03				
1.300E+01	-2.31E-03				
1.400E+01	-2.32E-03				
1.500E+01	-2.34E-03				
1.600E+01	-2.36E-03				
1.700E+01	-2.37E-03				
1.800E+01	-2.39E-03				
1.900E+01	-2.40E-03				
2.000E+01	-2.42E-03				
2.100E+01	-2.44E-03				
2.200E+01	-2.45E-03				
2.300E+01	-2.47E-03				
2.400E+01	-2.49E-03				
2.500E+01	-2.50E-03				
2.600E+01	-2.52E-03				
2.700E+01	-2.53E-03				
2.800E+01	-2.55E-03				
2.900E+01	-2.57E-03				
3.000E+01	-2.58E-03				

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:1	= 7.651E-01	0:2	= 1.000E+00	0:100	= 1.500E+01

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT					
ELEMENT	0:Q1	0:Q2	0:Q3	0:Q4	0:Q5
MODEL	0:NPN	0:NPN	0:NPN	0:NPN	0:NPN
IB	3.515E-06	3.515E-06	3.515E-06	3.515E-06	3.515E-06
IC	7.030E-04	7.030E-04	7.042E-04	7.042E-04	7.042E-04
VBE	7.651E-01	7.651E-01	7.651E-01	7.651E-01	7.651E-01
VCE	7.651E-01	7.651E-01	1.000E+00	1.000E+00	1.000E+00
VBC	0.	0.	-2.349E-01	-2.349E-01	-2.349E-01
VS	-7.651E-01	-7.651E-01	-1.000E+00	-1.000E+00	-1.000E+00
POWER	5.405E-04	5.405E-04	7.069E-04	7.069E-04	7.069E-04
BETAD	2.000E+02	2.000E+02	2.003E+02	2.003E+02	2.003E+02
GM	2.717E-02	2.717E-02	2.722E-02	2.722E-02	2.722E-02
RPI	7.358E+03	7.358E+03	7.358E+03	7.358E+03	7.358E+03
RX	0.	0.	0.	0.	0.
RO	1.849E+05	1.849E+05	1.849E+05	1.849E+05	1.849E+05
BETAAC	1.999E+02	1.999E+02	2.003E+02	2.003E+02	2.003E+02

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(2)/VO = 1.000E+00
INPUT RESISTANCE AT VO = 6.164E+04

4.3

From Table (2.4),

$$\begin{aligned}
 K' &= \mu_n C_{ox} \\
 &= \frac{450 \times 3.9 \times 8.86 \times 10^{-14}}{0.08 \times 10^{-5}} \\
 &= 194 \mu A/V^2
 \end{aligned}$$

$$I_{OUT} = 50 \mu A (1 + \lambda \Delta V_{DS})$$

From condition (c), $\lambda \Delta V_{DS} \leq 0.01$

$$\text{and } \Delta V_{DS} = 1V \Rightarrow \lambda \leq 0.01 V^{-1}$$

From conditions (a) and (b)

$$50 \mu A = \frac{K'}{2} \frac{W}{L_{eff}} (V_{GS} - V_t)^2 \text{ where}$$

$$V_{GS} - V_t = 0.2V$$

$$50 \mu A = \frac{194}{2} \frac{W}{L_{eff}} (0.2)^2 \Rightarrow \frac{W}{L_{eff}} = 12.9$$

$$\lambda \leq \frac{1}{100V}; \text{ Also from the table } \frac{d\lambda_d}{dV_{DS}} = 0.02 \mu m/V$$

$$\lambda = \frac{1}{V_A} = \frac{d\lambda_d/dV_{DS}}{L_{eff}} \leq \frac{1}{100V}$$

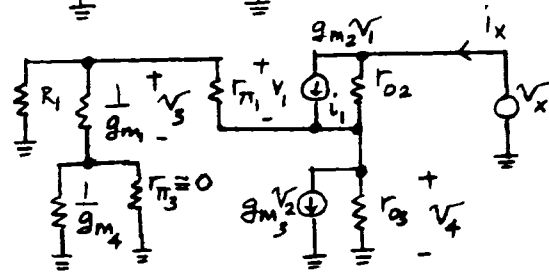
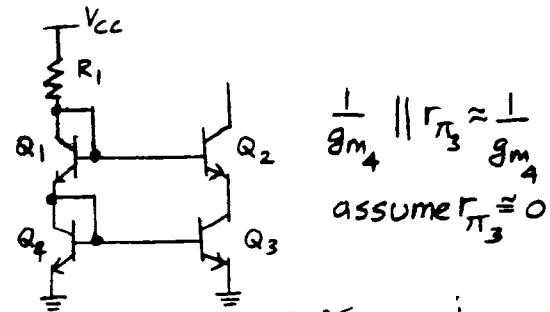
$$\Rightarrow L_{eff} \geq 2 \mu m$$

$$L_{drawn} = 2 \mu m + 2(0.09) = 2.18 \mu m \approx 2.2 \mu m$$

The minimum length that satisfies the constraints minimizes the required gate area

$$\text{Then } W = 12.9 \times 2.2 \mu m = 28 \mu m$$

4.4



$$i_1 = \frac{V_4}{r_{\pi 1} + R_1 \parallel \frac{2}{g_{m1}}} = \frac{V_4}{R}$$

$$I_{C1} = I_{C2} = I_{C3} = I_{C4}$$

$$g_{m1} = g_{m2} = g_{m3} = g_{m4} = g_m$$

$$r_{o1} = r_{o2} = r_{o3} = r_{o4} = r_o$$

$$V_2 = i_1 \frac{R_1}{R_1 + \frac{2}{g_m}} \cdot \frac{1}{g_m} = K i_1 \frac{1}{g_m}$$

$$V_1 = -i_1 r_{\pi 1}$$

$$\begin{aligned}
 g_{m2} V_1 + \frac{V_x - V_4}{r_{o2}} &= i_1 + \frac{V_4}{r_{o3}} + g_{m3} V_2 \\
 &= i_1 + \frac{V_4}{r_{o3}} + K i_1
 \end{aligned}$$

$$-\beta i_1 + \frac{V_x}{r_o} - \frac{V_4}{r_o} = (1 + K) i_1 + \frac{V_4}{r_o}$$

$$i_1 \left(\beta + 1 + K + \frac{2R}{r_o} \right) = \frac{V_x}{r_o}$$

$$\begin{aligned}
 i_x &= g_{m2} V_1 + \frac{V_x - V_4}{r_{o2}} \\
 &= -g_{m2} r_{\pi 1} i_1 + \frac{V_x}{r_{o2}} - \frac{V_4}{r_{o2}} \\
 &= -\beta i_1 + \frac{V_x}{r_o} - \frac{R}{r_o} i_1
 \end{aligned}$$

$$= \frac{V_x}{r_o} - \left(\beta + \frac{R}{r_o} \right) \frac{V_x}{r_o} \frac{1}{\beta + 1 + K + \frac{2R}{r_o}}$$

$$\frac{i_x}{V_x} = \frac{1}{r_o} \left(1 - \frac{\beta + \frac{R}{r_o}}{\beta + 1 + K + \frac{2R}{r_o}} \right)$$

$$= \frac{1}{r_o} \frac{\beta + 1 + K + \frac{2R}{r_o} - \beta - \frac{R}{r_o}}{\beta + 1 + K + \frac{2R}{r_o}}$$

$$= \frac{1}{r_o} \frac{1 + K + \frac{R}{r_o}}{\beta + 1 + K + \frac{2R}{r_o}}$$

$$R_o = \frac{V_x}{i_x} = r_o \frac{\beta + 1 + K + \frac{2R}{r_o}}{1 + K + \frac{R}{r_o}}$$

$$K = \frac{R_1}{R_1 + \frac{2}{g_m}} = 1 \text{ for } R_1 \rightarrow \infty$$

$$R = r_{\pi_1} + R_1 \parallel \frac{2}{g_{m_1}} \cong r_{\pi_1} \text{ for } R_1 \rightarrow \infty$$

$$\frac{r_{\pi_1}}{r_o} \ll 1$$

$$R_o \cong r_o \frac{2 + \beta}{2} \cong \frac{\beta r_o}{2} \text{ for large } R$$

$$V_{BE} = V_T \ln \frac{I_C}{I_S}$$

$$I_C = \frac{5 - 2(0.8)}{10 \text{ k}} = 340 \mu\text{A}$$

$$V_{BE} = 26 \text{ mV} \ln \frac{340 \mu\text{A}}{5 \text{ fA}} = 0.65 \text{ V}$$

$$I_C = \frac{5 - 2(0.65)}{10 \text{ k}} = 370 \mu\text{A}$$

$$\frac{1}{g_m} = 70 \Omega$$

$$K = \frac{10,000}{10,140} = 0.986$$

$$R = r_{\pi_1} + R_1 \parallel \frac{2}{g_{m_1}} = 200(70) + 10 \text{ k} \parallel 140$$

$$= 14 \text{ k} + 140 = 14.2 \text{ k}$$

$$r_o = \frac{130}{0.37} \text{ k}\Omega = 351 \text{ k}\Omega$$

$$R_o = (351 \text{ k}) \frac{200 + 1 + 0.99 + 2 \frac{14.2}{351}}{1 + 0.99 + \frac{14.2}{351}}$$

$$= 34.9 \text{ M}\Omega \text{ very close to } \frac{\beta r_o}{2}$$

R_o will decrease when Q_2 is saturated.

$$V_o = V_{BE(on)} + V_{CE(sat)}$$

$$\cong 0.65 + 0.1 = 0.75 \text{ V}$$

BJT CASCODE CURRENT MIRROR

VCC 100 0 5

R1 100 2 10K

Q1 2 2 3 NPN

Q2 5 2 4 NPN

Q3 4 3 0 NPN

Q4 3 3 0 NPN

VO 5 0 2

.MODEL NPN NPN IS=5E-15 BF=200 RB=200 VAF=130

.OPTIONS NOMOD NOPAGE

.WIDTH OUT=80

.OP

.DC VO 0 5 0.2

.PLOT I(VO)

.TF V(5) VO

.END

***** DC TRANSFER CURVES TNOM= 27.000 TEMP= 27.000

VOLT	I(VO)					
(A)		-1.000E-03	-5.000E-04	0.	5.000E-04	1.000E-03
0.	4.26E-04	+	+	+	+	+
2.000E-01	4.06E-04	+	+	+	+	+
4.000E-01	3.61E-04	+	+	+	+	+
6.000E-01	-2.23E-05	+	+	+	+	+
8.000E-01	-3.61E-04	+	+	+	+	+
1.000E+00	-3.63E-04	+	+	+	+	+
1.200E+00	-3.63E-04	+	+	+	+	+
1.400E+00	-3.63E-04	+	+	+	+	+
1.600E+00	-3.63E-04	+	+	+	+	+
1.800E+00	-3.63E-04	+	+	+	+	+
2.000E+00	-3.63E-04	+	+	+	+	+
2.200E+00	-3.63E-04	+	+	+	+	+
2.400E+00	-3.63E-04	+	+	+	+	+
2.600E+00	-3.63E-04	+	+	+	+	+
2.800E+00	-3.63E-04	+	+	+	+	+
3.000E+00	-3.63E-04	+	+	+	+	+
3.200E+00	-3.63E-04	+	+	+	+	+
3.400E+00	-3.63E-04	+	+	+	+	+
3.600E+00	-3.63E-04	+	+	+	+	+
3.800E+00	-3.63E-04	+	+	+	+	+
4.000E+00	-3.63E-04	+	+	+	+	+
4.200E+00	-3.63E-04	+	+	+	+	+
4.400E+00	-3.63E-04	+	+	+	+	+
4.600E+00	-3.63E-04	+	+	+	+	+
4.800E+00	-3.63E-04	+	+	+	+	+
5.000E+00	-3.63E-04	+	+	+	+	+

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:2	= 1.294E+00	0:3	= 6.473E-01	0:4	= 6.477E-01
+0:5	= 2.000E+00	0:100	= 5.000E+00		

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT

ELEMENT	0:Q1	0:Q2	0:Q3	0:Q4
MODEL	0:NPN	0:NPN	0:NPN	0:NPN
IB	1.834E-06	1.806E-06	1.825E-06	1.825E-06
IC	3.669E-04	3.633E-04	3.651E-04	3.651E-04
VBE	6.475E-01	6.471E-01	6.473E-01	6.473E-01
VCE	6.475E-01	1.352E+00	6.477E-01	6.473E-01
VBC	0.	-7.052E-01	-4.021E-04	0.
VS	-1.294E+00	-2.000E+00	-6.477E-01	-6.473E-01
POWER	2.387E-04	4.924E-04	2.376E-04	2.375E-04
BETAD	2.000E+02	2.010E+02	2.000E+02	2.000E+02
GM	1.418E-02	1.404E-02	1.411E-02	1.411E-02
RPI	1.410E+04	1.431E+04	1.417E+04	1.417E+04
RX	2.000E+02	2.000E+02	2.000E+02	2.000E+02
RO	3.543E+05	3.598E+05	3.561E+05	3.561E+05
BETAAC	1.999E+02	2.010E+02	1.999E+02	1.999E+02

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(5)/VO	= 1.000E+00
INPUT RESISTANCE AT VO	= 3.622E+07

BJT CASCODE CURRENT MIRROR

* (BETA REDUCED BY 50 PERCENT)

VCC 100 0 5

R1 100 2 10K

Q1 2 2 3 NPN

Q2 5 2 4 NPN

Q3 4 3 0 NPN

Q4 3 3 0 NPN

VO 5 0 2

.MODEL NPN NPN IS=5E-15 BF=100 RB=200 VAF=130

.OPTIONS NOMOD NOPAGE

.WIDTH OUT=80

.OP

.DC VO 0 5 0.2

.PLOT I(VO)

.TF V(5) VO

.END

***** DC TRANSFER CURVES TNOM= 27.000 TEMP= 27.000

VOLT	I(VO)					
(A)		-1.000E-03	-5.000E-04	0.	5.000E-04	1.000E-03
0.	4.26E-04	+	+	+	+	+
2.000E-01	4.06E-04	+	+	+	+	+
4.000E-01	3.61E-04	+	+	+	+	+
6.000E-01	-1.95E-05	+	+	+	+	+
8.000E-01	-3.54E-04	+	+	+	+	+
1.000E+00	-3.56E-04	+	+	+	+	+
1.200E+00	-3.56E-04	+	+	+	+	+
1.400E+00	-3.56E-04	+	+	+	+	+
1.600E+00	-3.56E-04	+	+	+	+	+
1.800E+00	-3.56E-04	+	+	+	+	+
2.000E+00	-3.56E-04	+	+	+	+	+
2.200E+00	-3.56E-04	+	+	+	+	+
2.400E+00	-3.56E-04	+	+	+	+	+
2.600E+00	-3.56E-04	+	+	+	+	+
2.800E+00	-3.56E-04	+	+	+	+	+
3.000E+00	-3.56E-04	+	+	+	+	+
3.200E+00	-3.56E-04	+	+	+	+	+
3.400E+00	-3.56E-04	+	+	+	+	+
3.600E+00	-3.56E-04	+	+	+	+	+
3.800E+00	-3.56E-04	+	+	+	+	+
4.000E+00	-3.56E-04	+	+	+	+	+
4.200E+00	-3.56E-04	+	+	+	+	+
4.400E+00	-3.56E-04	+	+	+	+	+
4.600E+00	-3.56E-04	+	+	+	+	+
4.800E+00	-3.56E-04	+	+	+	+	+
5.000E+00	-3.56E-04	+	+	+	+	+

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:2	= 1.294E+00	0:3	= 6.473E-01	0:4	= 6.480E-01
+0:5	= 2.000E+00	0:100	= 5.000E+00		

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT

ELEMENT	0:Q1	0:Q2	0:Q3	0:Q4
MODEL	0:NPN	0:NPN	0:NPN	0:NPN
IB	3.633E-06	3.543E-06	3.598E-06	3.598E-06
IC	3.633E-04	3.562E-04	3.598E-04	3.598E-04
VBE	6.476E-01	6.469E-01	6.473E-01	6.473E-01
VCE	6.476E-01	1.352E+00	6.480E-01	6.473E-01
VBC	0.	-7.051E-01	-6.686E-04	0.
VS	-1.294E+00	-2.000E+00	-6.480E-01	-6.473E-01
POWER	2.376E-04	4.839E-04	2.355E-04	2.352E-04
BETAD	1.000E+02	1.005E+02	1.000E+02	1.000E+02
GM	1.405E-02	1.377E-02	1.391E-02	1.391E-02
RPI	7.118E+03	7.299E+03	7.189E+03	7.189E+03
RX	2.000E+02	2.000E+02	2.000E+02	2.000E+02
RO	3.578E+05	3.669E+05	3.613E+05	3.613E+05
BETAAC	9.998E+01	1.005E+02	9.998E+01	9.998E+01

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(5)/VO	= 1.000E+00
INPUT RESISTANCE AT VO	= 1.892E+07

4.5

$$L_{eff} = 1\mu m - 2(0.09\mu m) = 0.82\mu m$$

$$r_o = \frac{1}{\lambda I_D} \quad \text{where } \lambda = \frac{d\lambda_d}{dV_{DS}} / L_{eff}$$

$$\lambda = \frac{0.02}{0.82} = 0.024 \text{ V}^{-1}$$

$$r_o = \frac{1}{0.024(100\mu A)} = 417 \text{ k}\Omega$$

$$g_m = \sqrt{2k' \frac{W}{L_{eff}} I_D} = \sqrt{2(194)\left(\frac{100}{0.82}\right)100}$$

$$= 2.18 \text{ mA/V}$$

$$R_o = r_{o2} [1 + (g_{m2} + g_{mb2})r_{o1}] + r_{o1}$$

Here, $g_{mb2} = 0$ by assumption

$$R_o = r_{o2} (g_{m2} r_{o1}) = 417 \text{ k} (2.18 \text{ m} \cdot 417 \text{ k})$$

$$= 379 \text{ M}\Omega$$

CASCODE CURRENT MIRROR

```
VDD 100 0 3
IIN 100 3 100U
VO 5 0 3
M1 1 4 0 0 CMOSN W=100U L=1U
M2 5 3 1 1 CMOSN W=100U L=1U
M3 3 3 4 4 CMOSN W=100U L=1U
M4 4 4 0 0 CMOSN W=100U L=1U
* NOTE THAT CONNECTING THE BODY TO THE SOURCE ELIMINATES
* THE BODY EFFECT.
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0.024 VTO=0.6 KP=194U LD=0.09U
* NOTE THAT LAMBDA = (DXD/DVDS)/LEFF = 0.02/0.82=0.0244
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VO 0 3 0.1
.PLOT DC I(VO)
.TF V(5) VO
.END
```

***** DC TRANSFER CURVES TNOM= 27.000 TEMP= 27.000

VOLT	I(VO)						
1A		-1.500E-04	-1.000E-04	-5.000E-05	0.	5.000E-05	
0.	0.						
1.000E-01	-9.86E-05	+	A	+	+	+	+
2.000E-01	-9.88E-05	+	A	+	+	+	+
3.000E-01	-9.91E-05	+	A	+	+	+	+
4.000E-01	-9.93E-05	+	A	+	+	+	+
5.000E-01	-9.95E-05	+	A	+	+	+	+
6.000E-01	-9.97E-05	+	A	+	+	+	+
7.000E-01	-9.99E-05	+	A	+	+	+	+
8.000E-01	-1.00E-04	+	A	+	+	+	+
9.000E-01	-1.00E-04	+	A	+	+	+	+
1.000E+00	-1.00E-04	+	A	+	+	+	+
1.100E+00	-1.00E-04	+	A	+	+	+	+
1.200E+00	-1.00E-04	+	A	+	+	+	+
1.300E+00	-1.00E-04	+	A	+	+	+	+
1.400E+00	-1.00E-04	+	A	+	+	+	+
1.500E+00	-1.00E-04	+	A	+	+	+	+
1.600E+00	-1.00E-04	+	A	+	+	+	+
1.700E+00	-1.00E-04	+	A	+	+	+	+
1.800E+00	-1.00E-04	+	A	+	+	+	+
1.900E+00	-1.00E-04	+	A	+	+	+	+
2.000E+00	-1.00E-04	+	A	+	+	+	+
2.100E+00	-1.00E-04	+	A	+	+	+	+
2.200E+00	-1.00E-04	+	A	+	+	+	+
2.300E+00	-1.00E-04	+	A	+	+	+	+
2.400E+00	-1.00E-04	+	A	+	+	+	+
2.500E+00	-1.00E-04	+	A	+	+	+	+
2.600E+00	-1.00E-04	+	A	+	+	+	+
2.700E+00	-1.00E-04	+	A	+	+	+	+
2.800E+00	-1.00E-04	+	A	+	+	+	+
2.900E+00	-1.00E-04	+	A	+	+	+	+
3.000E+00	-1.00E-04	+	A	+	+	+	+

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:1	= 6.929E-01	0:3	= 1.382E+00	0:4	= 6.912E-01
+0:5	= 3.000E+00	0:100	= 3.000E+00		

**** MOSFETS

SUBCKT				
ELEMENT	0:M1	0:M2	0:M3	0:M4
MODEL	0:CMOSN	0:CMOSN	0:CMOSN	0:CMOSN
ID	1.000E-04	1.000E-04	1.000E-04	1.000E-04
IBS	0.	0.	0.	0.
IBD	-6.929E-15	-2.307E-14	-6.912E-15	-6.912E-15
VGS	6.912E-01	6.895E-01	6.912E-01	6.912E-01
VDS	6.929E-01	2.307E+00	6.912E-01	6.912E-01
VBS	0.	0.	0.	0.
VTH	6.000E-01	6.000E-01	6.000E-01	6.000E-01
VDSAT	9.119E-02	8.950E-02	9.119E-02	9.119E-02
BETA	2.405E-02	2.497E-02	2.405E-02	2.405E-02
GAM EFF	0.	0.	0.	0.
GM	2.193E-03	2.235E-03	2.193E-03	2.193E-03
GDS	2.361E-06	2.274E-06	2.361E-06	2.361E-06
GMB	0.	0.	0.	0.

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(5)/VO		= 1.000E+00
INPUT RESISTANCE AT	VO	= 4.170E+08

4-6

Look at M2

$$V_{DS_{M2}} = V_{OUT} - V_{DS_{M1}} = V_{OUT} - V_{GS_{M1}}$$

$$\begin{aligned} V_{GS_{M1}} &= V_t + \sqrt{\frac{2I_D}{K'W/L_{eff}}} \\ &= 0.6 + \sqrt{\frac{200\mu}{194.4 \cdot 100\% \cdot 0.82}} \\ &= 0.692 \text{ V} \end{aligned}$$

$$\begin{aligned} V_{DS_{ACT_{M2}}} &= V_{GS} - V_t \\ &= 0.692 - 0.6 = 0.092 \text{ V} \end{aligned}$$

Assume no body effect on V_t

$$V_{OUT} = 2 \text{ V}$$

$$V_{DS} = 2 - 0.692 = 1.308 \text{ V}$$

$$V_{DS_{ACT}} = 0.092 \text{ V}$$

$$V_{DS} - V_{DS_{ACT}} = 1.216 \text{ V}$$

From (1.261),

$$\begin{aligned} I_{DB} &= 5 (1.216) (100\mu) e^{-30/1.216} \\ &= 11.7 \text{ fA} \end{aligned}$$

From (1.262),

$$g_{db} = 30 \frac{11.7 \text{ fA}}{(1.216)^2} = 0.238 \frac{\text{pA}}{\text{V}}$$

$$r_{db} = \frac{1}{g_{db}} = 4200 \text{ } \Omega$$

$$R_o = 379 \text{ M}\Omega \parallel 4200 \text{ } \Omega = 379 \text{ M}\Omega$$

No change due to substrate leakage

$$V_{OUT} = 3 \text{ V}$$

$$V_{DS} = 3 - 0.692 = 2.308 \text{ V}$$

$$V_{DS} - V_{DS_{ACT}} = 2.216 \text{ V}$$

$$\begin{aligned} I_{DB} &= 2 (2.216) (100\mu) e^{-30/2.216} \\ &= 1.46 \text{ nA} \end{aligned}$$

$$g_{db} = 29.7 \text{ nA/V}$$

$$r_{db} = 33.7 \text{ M}\Omega$$

$$R_o = 33.7 \text{ M}\Omega \parallel 379 \text{ M}\Omega = 30.9 \text{ M}\Omega$$

Output resistance dominated by substrate leakage.

4.7

From condition (a), $V_{o\min} = 0.2 \text{ V}$

This is split across M_1 and M_2

Therefore, $V_{ov} = V_{GS} - V_t = 0.1 \text{ V}$

From this and condition (b),

$$50 \mu\text{A} = \frac{194 \mu}{2} \left(\frac{W}{L_{\text{eff}}} \right) (0.1)^2$$

$$\Rightarrow \frac{W}{L_{\text{eff}}} = 51.5$$

$$r_o = \frac{1}{\lambda I_D} \quad \text{where } \lambda = \frac{d\lambda_d}{dV_{os}} / L_{\text{eff}}$$

$$\text{So, } r_o = \frac{L_{\text{eff}}}{50 \mu (0.02 \frac{\mu\text{m}}{\text{V}})} = \frac{L_{\text{eff}}}{1 \times 10^{-12}}$$

$$R_o = \frac{\Delta V_{out}}{\Delta I_{out}} = \frac{1 \text{ V}}{0.0002 (I_D)} = \frac{1 \text{ V}}{0.0002 (50 \mu)}$$

$$= 100 \text{ M}\Omega$$

From (4.50), $R_o \cong r_{o2} g_{m2} r_{o1}$

$$\Rightarrow R_o \cong \left(\frac{L_{\text{eff}}}{10^{-12}} \right)^2 \sqrt{2(194)(51.5)(50)}$$

$$= \frac{L_{\text{eff}}^2}{10^{-21}} = 100 \text{ M}\Omega$$

Therefore, $L_{\text{eff}} = 0.32 \mu\text{m}$

$$L_{\text{drawn}} = L_{\text{eff}} + 2L_d = 0.32 + 2(0.09)$$

$$= 0.5 \mu\text{m}$$

$$W = (51.5)(0.32) = 16.5 \mu\text{m}$$

CASCODE CURRENT MIRROR WITH LEVEL SHIFT

VDD 100 0 3
VO 2 0 0.2
IR 100 4 51.84U

* NOTE THAT IR > 50 UA BECAUSE THIS CURRENT MIRROR HAS A
* NONZERO SYSTEMATIC GAIN ERROR. IR = 51.9 UA IS CHOSEN
* BY TRIAL AND ERROR TO FORCE THE OUTPUT CURRENT TO BE 50 UA,
* AS GIVEN IN THE PROBLEM.

* IN THE HAND CALCULATION, THE REQUIRED WIDTH WAS CALCULATED
* TO BE 16.5 MICRONS; HOWEVER, TRIAL AND ERROR IN SPICE SHOWS
* THAT THE WIDTH HAS TO BE INCREASED TO 18 MICRONS TO OPERATE
* M1 AND M2 BARELY IN THE ACTIVE REGION. THIS DIFFERENCE
* STEMS FROM THE OBSERVATION THAT ALL THE TRANSISTORS DO NOT
* OPERATE AT EQUAL CURRENTS. TO OVERCOME THIS PROBLEM
* IN PRACTICE, THE W/L OF M4 WOULD BE REDUCED TO INCREASE
* THE DRAIN-SOURCE VOLTAGE ON M1. THIS CHANGE WOULD ALSO BE
* USED TO MAKE SURE THAT M1 OPERATES SLIGHTLY BEYOND THE EDGE
* OF THE TRIODE REGION EVEN WHEN BODY EFFECT IS TAKEN
* INTO ACCOUNT.

M1 1 3 0 0 CMOSN W=18U L=0.5U
M2 2 6 1 1 CMOSN W=18U L=0.5U
M3 3 3 0 0 CMOSN W=18U L=0.5U
M4A 4 4 A3 A3 CMOSN W=18U L=0.5U
M4B A3 4 B3 B3 CMOSN W=18U L=0.5U
M4C B3 4 C3 C3 CMOSN W=18U L=0.5U
M4D C3 4 3 3 CMOSN W=18U L=0.5U

* NOTE THAT 4 TRANSISTORS ARE USED IN SERIES TO BUILD M4
* TO DESENSITIZE THE CIRCUIT TO VARIATIONS IN DELTA W
* AND DELTA L. IN PRACTICE, 5 OR MORE TRANSISTORS WOULD BE
* USED TO PUSH M1 PAST THE EDGE OF SATURATION AND TO OVERCOME
* BODY-EFFECT MISMATCHES.

M5 100 4 6 6 CMOSN W=18U L=0.5U
M6 6 3 0 0 CMOSN W=18U L=0.5U

* NOTE THAT CONNECTING THE BODY TO THE SOURCE ELIMINATES
* THE BODY EFFECT.

* MODEL CMOSN NMOS LEVEL=1 LAMBDA=0.0625 VTO=0.6 KP=194U LD=0.09U

* NOTE THAT LAMBDA = (DMD/DVDS)/LEFF = 0.02/0.32

.OPTIONS NOMOD NOPAGE

.WIDTH OUT=80

.OP

.DC VO 0 3 0.1

.PLOT DC I(VO)

.TF V(2) VO

.END

***** DC TRANSFER CURVES TNOM= 27.000 TEMP= 27.000

VOLT	I(VO)
-6.000E-05	-4.000E-05
-4.000E-05	-2.000E-05
-2.000E-05	0.
0.	2.000E-05
2.000E-05	4.000E-05
4.000E-05	6.000E-05
6.000E-05	8.000E-05
8.000E-05	1.000E-04
1.000E-04	1.200E-04
1.200E-04	1.400E-04
1.400E-04	1.600E-04
1.600E-04	1.800E-04
1.800E-04	2.000E-04
2.000E-04	2.200E-04
2.200E-04	2.400E-04
2.400E-04	2.600E-04
2.600E-04	2.800E-04
2.800E-04	3.000E-04
3.000E-04	3.200E-04
3.200E-04	3.400E-04
3.400E-04	3.600E-04
3.600E-04	3.800E-04
3.800E-04	4.000E-04
4.000E-04	4.200E-04
4.200E-04	4.400E-04
4.400E-04	4.600E-04
4.600E-04	4.800E-04
4.800E-04	5.000E-04
5.000E-04	5.200E-04
5.200E-04	5.400E-04
5.400E-04	5.600E-04
5.600E-04	5.800E-04
5.800E-04	6.000E-04
6.000E-04	6.200E-04
6.200E-04	6.400E-04
6.400E-04	6.600E-04
6.600E-04	6.800E-04
6.800E-04	7.000E-04
7.000E-04	7.200E-04
7.200E-04	7.400E-04
7.400E-04	7.600E-04
7.600E-04	7.800E-04
7.800E-04	8.000E-04
8.000E-04	8.200E-04
8.200E-04	8.400E-04
8.400E-04	8.600E-04
8.600E-04	8.800E-04
8.800E-04	9.000E-04
9.000E-04	9.200E-04
9.200E-04	9.400E-04
9.400E-04	9.600E-04
9.600E-04	9.800E-04
9.800E-04	1.000E-03

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:1	= 1.021E-01 0:2		= 2.000E-01 0:3		= 6.954E-01
+0:4	= 1.489E+00 0:6		= 7.975E-01 0:100		= 3.000E+00
+0:A3	= 7.938E-01 0:B3		= 7.529E-01 0:C3		= 7.217E-01

**** MOSFETS

SUBCCT

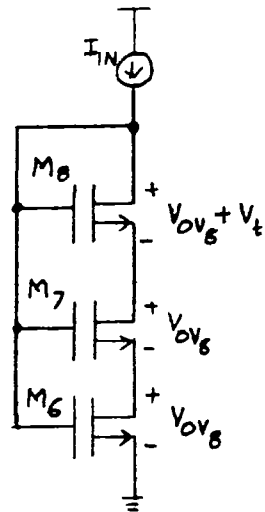
ELEMENT	0:M1	0:M2	0:M3	0:M4A	0:M4B
MODEL	0:CMOSN	0:CMOSN	0:CMOSN	0:CMOSN	0:CMOSN
ID	5.000E-05	5.000E-05	5.184E-05	5.184E-05	5.184E-05
IBS	0.	0.	0.	0.	0.
IBD	-1.021E-15	-9.790E-16	-6.954E-15	-6.954E-15	-4.089E-16
VGS	6.954E-01	6.954E-01	6.954E-01	6.954E-01	7.363E-01
VDS	1.021E-01	9.790E-02	6.954E-01	6.954E-01	4.089E-02
VBS	0.	0.	0.	0.	0.
VTH	6.000E-01	6.000E-01	6.000E-01	6.000E-01	6.000E-01
VDSAT	9.542E-02	9.543E-02	9.542E-02	9.542E-02	4.089E-02
BETA	1.098E-02	1.098E-02	1.139E-02	1.139E-02	1.094E-02
GAM EFF	0.	0.	0.	0.	0.
GM	1.048E-03	1.048E-03	1.087E-03	1.087E-03	4.474E-04
GDS	3.105E-06	3.106E-06	3.105E-06	3.105E-06	1.047E-03
GMB	0.	0.	0.	0.	0.

SUBCCT

ELEMENT	0:M4C	0:M4D	0:M5	0:M6
MODEL	0:CMOSN	0:CMOSN	0:CMOSN	0:CMOSN
ID	5.184E-05	5.184E-05	5.216E-05	5.216E-05
IBS	0.	0.	0.	0.
IBD	-3.121E-16	-2.625E-16	-2.202E-14	-7.975E-15
VGS	7.675E-01	7.938E-01	6.917E-01	6.954E-01
VDS	3.121E-02	2.625E-02	2.202E+00	7.975E-01
VBS	0.	0.	0.	0.
VTH	6.000E-01	6.000E-01	6.000E-01	6.000E-01
VDSAT	3.121E-02	2.625E-02	9.167E-02	9.542E-02
BETA	1.093E-02	1.093E-02	1.241E-02	1.146E-02
GAM EFF	0.	0.	0.	0.
GM	3.412E-04	2.870E-04	1.138E-03	1.093E-03
GDS	1.494E-03	1.834E-03	2.865E-06	3.105E-06
GMB	0.	0.	0.	0.

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(2)/VO		= 1.000E+00
INPUT RESISTANCE AT	VO	= 1.092E+08

4.8

M_8 operates in active region

M_6 and M_7 operate in triode region.

$$I = \frac{k'}{2} \left(\frac{W}{L} \right)_8 (V_{GS8} - V_t)^2$$

$$I = \frac{k'}{2} \left(\frac{W}{L} \right)_7 [2(V_{GS7} - V_t)V_{DS7} - V_{DS7}^2]$$

$$I = \frac{k'}{2} \left(\frac{W}{L} \right)_6 [2(V_{GS6} - V_t)V_{DS6} - V_{DS6}^2]$$

$$\left(\frac{W}{L} \right)_8 (V_{OV8})^2 = \left(\frac{W}{L} \right)_7 [2(2V_{OV8})V_{OV8} - V_{OV8}^2]$$

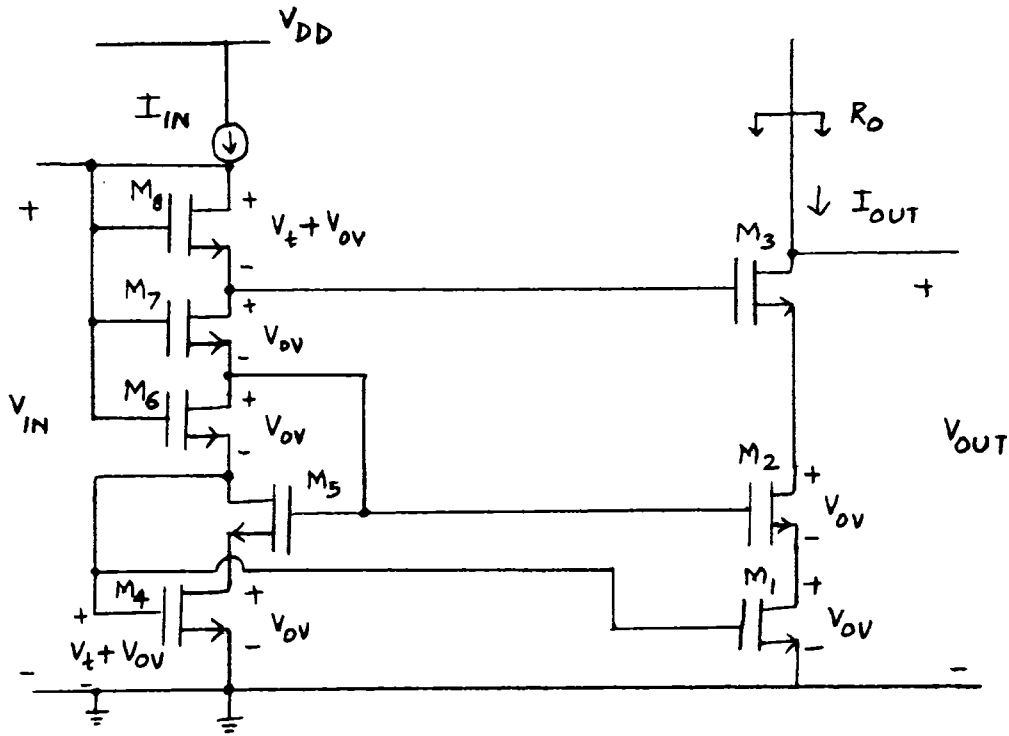
$$= \left(\frac{W}{L} \right)_6 [2(3V_{OV8})V_{OV8} - V_{OV8}^2]$$

$$\left(\frac{W}{L} \right)_8 (V_{OV8})^2 = \left(\frac{W}{L} \right)_7 (3V_{OV8}^2) = \left(\frac{W}{L} \right)_6 (5V_{OV8}^2)$$

$$\left(\frac{W}{L} \right)_7 = \frac{1}{3} \left(\frac{W}{L} \right)_8$$

$$\left(\frac{W}{L} \right)_6 = \frac{1}{5} \left(\frac{W}{L} \right)_8$$

In practice, $\left(\frac{W}{L} \right)_6$ and $\left(\frac{W}{L} \right)_7$ would be even smaller to increase V_{DS6} and V_{DS7} slightly so that all the transistors in the output branch of a current mirror using the circuit operate in the active region



$$\begin{aligned} V_{IN} &= V_{GS4} + V_{DS6} + V_{DS7} + V_{GS8} \\ &= V_t + V_{OV} + V_{OV} + V_{OV} + V_t + V_{OV} \\ &= 2V_t + 4V_{OV} \end{aligned}$$

$$\begin{aligned} V_{OUT(min)} &= V_{DS1} + V_{DS2} + V_{DS3(min)} \\ &= V_{OV} + V_{OV} + V_{OV} \\ &= 3V_{OV} \end{aligned}$$

Systematic gain error = 0
(because $V_{DS4} = V_{DS1} = V_{OV}$)

Assuming M_1 - M_3 operate in the active region, the output resistance [ignoring the body effect as in (4.53)] is

$$R_0 \approx r_0 (g_m r_0)^2$$

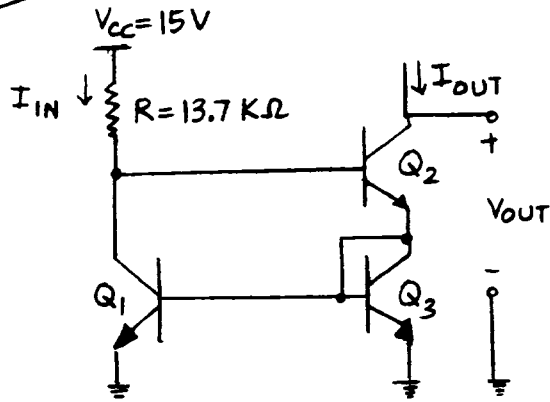
where, $g_m = g_{m_1} = g_{m_2} = g_{m_3}$

and

$$r_0 = r_{01} = r_{02} = r_{03}$$

if $M_1 = M_2 = M_3$.

4.9



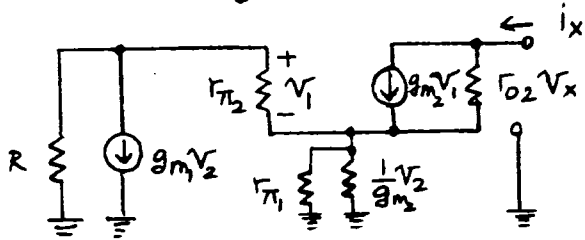
From (4.100)

$$I_{OUT} = I_{C2} = I_{IN} \left[1 - \frac{2}{\beta^2 + 2\beta + 2} \right]$$

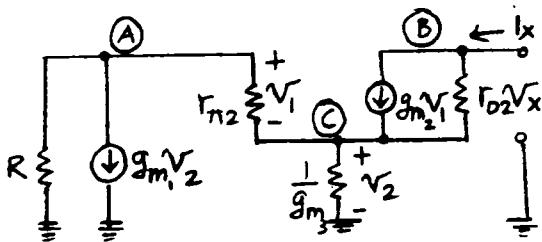
$$I_{IN} = \frac{15 - 2 \times 0.7}{13.7 \text{ K}} = 0.993 \text{ mA} \approx 1 \text{ mA}$$

$$\therefore I_{OUT} = 0.993 \left[1 - \frac{2}{200^2 + 2 \times 200 + 2} \right] \approx 0.993 \text{ mA} \approx 1 \text{ mA}$$

The small signal circuit is:



Each transistor has the same $I_C \approx 1 \text{ mA}$. $\therefore$ same r_{π} , g_m and r_o . Neglect $r_{\pi 1}$ compare to $1/g_{m3}$ circuit becomes:



$$\text{At } \textcircled{B} \quad i_x = g_m V_1 + \frac{V_x - V_2}{r_o} \rightarrow \textcircled{1}$$

$$\text{At } \textcircled{A} \quad \frac{V_1 + V_2}{R} + g_m V_2 + \frac{V_1}{r_{\pi}} = 0 \rightarrow \textcircled{2}$$

$$\text{At } \textcircled{C} \quad \frac{V_1}{r_{\pi}} + g_m V_1 + \frac{V_x - V_2}{r_o} = g_m V_2 \rightarrow \textcircled{3}$$

$$\therefore V_1 \left(\frac{1}{r_{\pi}} + g_m \right) + \frac{V_x}{r_o} = V_2 \left(g_m + \frac{1}{r_o} \right) \rightarrow \textcircled{4}$$

$$\text{From } \textcircled{2}, V_1 \left(\frac{1}{R} + \frac{1}{r_{\pi}} \right) = -V_2 \left(\frac{1}{R} + g_m \right)$$

$$\therefore V_1 = -V_2 \frac{1 + g_m R}{1 + \frac{R}{r_{\pi}}} \rightarrow \textcircled{5}$$

 $\textcircled{5}$ in $\textcircled{4}$:

$$-V_2 \frac{1 + g_m R}{1 + \frac{R}{r_{\pi}}} \left(\frac{1}{r_{\pi}} + g_m \right) + \frac{V_x}{r_o} = V_2 \left(g_m + \frac{1}{r_o} \right)$$

$$\therefore V_x = V_2 r_o \left[g_m + \frac{1}{r_o} + \frac{(g_m + \frac{1}{r_{\pi}})(1 + g_m R)}{1 + \frac{R}{r_{\pi}}} \right] \rightarrow \textcircled{6}$$

 $\textcircled{5}$ in $\textcircled{1}$:

$$i_x = -g_m V_2 \frac{1 + g_m R}{1 + \frac{R}{r_{\pi}}} + \frac{V_x}{r_o} - \frac{V_2}{r_o} \rightarrow \textcircled{7}$$

 $\textcircled{6}$ in $\textcircled{7}$:

$$\begin{aligned} \frac{i_x}{V_x} &= \frac{1}{r_o} - \frac{\left[\frac{1}{r_o} + g_m \frac{1 + g_m R}{1 + R/r_{\pi}} \right]}{r_o \left[g_m + \frac{1}{r_o} + \frac{(g_m + \frac{1}{r_{\pi}})(1 + g_m R)}{1 + R/r_{\pi}} \right]} \\ &= \frac{1}{r_o} \left[\frac{g_m (1 + R/r_{\pi}) + \frac{1}{r_{\pi}} (1 + g_m R)}{(g_m + \frac{1}{r_o}) (1 + \frac{R}{r_{\pi}}) + (g_m + \frac{1}{r_{\pi}}) (1 + g_m R)} \right] \end{aligned}$$

$$R_o = \frac{V_x}{i_x} = r_o \left[1 + \frac{\frac{1}{r_o} + \frac{1}{r_o} \frac{R}{r_{\pi}} + g_m (1 + g_m R)}{g_m + \frac{2}{r_o} + \frac{1}{r_{\pi}}} \right]$$

$$\approx r_o \left[1 + \frac{\frac{1}{r_o} \frac{r_{\pi}}{\beta_o} + \frac{1}{r_o} \frac{R}{\beta_o} + 1 + \frac{\beta_o R}{r_{\pi}}}{1 + 2R/r_{\pi}} \right]$$

$$\approx r_o \left[1 + \frac{1 + \frac{1}{g_m r_o} + g_m R}{1 + 2R/r_{\pi}} \right] \rightarrow \textcircled{8}$$

$$\left(\because g_m = \frac{\beta_o}{r_\pi} \gg \frac{1}{r_\pi}, g_m R = \frac{\beta_o R}{r_\pi} \gg \frac{R}{r_o \beta_o} \right)$$

In this problem $g_m = \frac{1 \text{ mA}}{26 \text{ mV}} = \frac{1}{26} \text{ S}$

$$r_\pi = \frac{\beta_o}{g_m} = 5.2 \text{ k}\Omega, R = 13.7 \text{ k}\Omega$$

$$r_o = \frac{130 \text{ V}}{1 \text{ mA}} = 130 \text{ k}\Omega$$

$$\therefore R_o = 130 \text{ k} \left[1 + \frac{528}{6.27} \right] = 11.1 \text{ M}\Omega$$

(If $R \rightarrow \infty$ then $R_o = r_o \left[1 + \frac{\beta_o}{2} \right]$)

If V_{out} changes by 5V then,

I_{out} changes by

$$\Delta I_{out} = \frac{\Delta V_{out}}{R} = \frac{5}{11.1} \text{ }\mu\text{A} = 0.45 \text{ }\mu\text{A}$$

The percentage change in I_{out} is

$$\frac{0.45 \times 10^{-6}}{10^{-3}} \times 100 = 0.045\%$$

```

WILSON CURRENT MIRROR
VCC 100 0 15
RBIAS 100 2 13.7K
Q1 2 3 0 NPN
Q2 4 2 3 NPN
Q3 3 3 0 NPN
VO 4 0 2
.MODEL NPN NPN IS=5E-15 BF=200 RB=200 VAF=130 RE=2
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VO 0 15 0.5
.PRINT I(VO)
.PLOT I(VO)
.TF V(2) VO
* RESULTS (BETA = 200)
* WHEN VOUT = 10 VOLTS, IOUT = 992.2 MICROAMPS
* WHEN VOUT = 5 VOLTS, IOUT = 991.7 MICROAMPS
* SO IOUT CHANGES BY 0.5 MICROAMPS OR 0.05 PERCENT
* AS VOUT INCREASES FROM 5 VOLTS TO 10 VOLTS
* ALSO RO = 11.0 MEGAOHMS
.END

***** DC TRANSFER CURVES TNOM= 27.000 TEMP= 27.000
VOLT I(VO)
(A) -1.000E-03 0. 1.000E-03 2.000E-03 3.000E-03
0. 1.031E-03
5.00E-01 9.923E-04
1.00E+00 -9.914E-04
1.50E+00 -9.914E-04
2.00E+00 -9.915E-04
2.50E+00 -9.915E-04
3.00E+00 -9.916E-04
3.50E+00 -9.916E-04
4.00E+00 -9.917E-04
4.50E+00 -9.917E-04
5.00E+00 -9.917E-04
5.50E+00 -9.918E-04
6.00E+00 -9.918E-04
6.50E+00 -9.919E-04
7.00E+00 -9.919E-04
7.50E+00 -9.920E-04
8.00E+00 -9.920E-04
8.50E+00 -9.920E-04
9.00E+00 -9.921E-04
9.50E+00 -9.921E-04
1.00E+01 -9.922E-04
1.05E+01 -9.922E-04
1.10E+01 -9.923E-04
1.15E+01 -9.923E-04
1.20E+01 -9.923E-04
1.25E+01 -9.924E-04
1.30E+01 -9.924E-04
1.35E+01 -9.924E-04
1.40E+01 -9.925E-04
1.45E+01 -9.925E-04
1.50E+01 -9.926E-04

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000
NODE =VOLTAGE NODE =VOLTAGE NODE =VOLTAGE
+0:2 = 1.351E+00 0:3 = 6.756E-01 0:4 = 2.000E+00
+0:100 = 1.500E+01

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT 0:Q1 0:Q2 0:Q3
MODEL 0:NPN 0:NPN 0:NPN
IB 4.931E-06 4.933E-06 4.933E-06
IC 9.913E-04 9.915E-04 9.865E-04
VBE 6.756E-01 6.757E-01 6.756E-01
VCE 1.351E+00 1.324E+00 6.756E-01
VBC -6.757E-01 -6.487E-01 0.
VS -1.351E+00 -2.000E+00 -6.756E-01
POWER 1.343E-03 1.316E-03 6.699E-04
BETAD 2.010E+02 2.010E+02 2.000E+02
GM 3.832E-02 3.833E-02 3.814E-02
RPI 5.245E+03 5.243E+03 5.243E+03
RX 2.000E+02 2.000E+02 2.000E+02
RO 1.318E+05 1.317E+05 1.317E+05
BETAAC 2.010E+02 2.009E+02 1.999E+02

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(2)/VO = -2.014E-04
 INPUT RESISTANCE AT VO = 1.098E+07
 OUTPUT RESISTANCE AT V(2) = 5.766E+01

WILSON CURRENT MIRROR (BETA REDUCED BY 50 PERCENT)

VCC 100 0 15
 RBIAS 100 2 13.7K
 Q1 2 3 0 NPN
 Q2 4 2 3 NPN
 Q3 3 3 0 NPN
 VO 4 0 2
 .MODEL NPN NPN IS=5E-15 BF=100 RB=200 VAF=130 RE=2
 .OPTIONS NOMOD NOPAGE
 .WIDTH OUT=80
 .OP
 .DC VO 0 15 0.5
 .PRINT I(VO)
 .PLOT I(VO)
 .TF V(2) VO
 * RESULTS (BETA = 100)
 * WHEN VOUT = 10 VOLTS, IOUT = 992.5 MICROAMPS
 * WHEN VOUT = 5 VOLTS, IOUT = 991.7 MICROAMPS
 * SO IOUT CHANGES BY 0.8 MICROAMPS OR 0.08 PERCENT
 * AS VOUT INCREASES FROM 5 VOLTS TO 10 VOLTS
 * ALSO RO = 6.0 MEGAOHMS
 .END

***** DC TRANSFER CURVES TNOM= 27.000 TEMP= 27.000

VOLT	I(VO)
0.	1.031E-03
5.00E+01	9.923E-04
1.00E+00	-9.911E-04
1.50E+00	-9.912E-04
2.00E+00	-9.913E-04
2.50E+00	-9.913E-04
3.00E+00	-9.914E-04
3.50E+00	-9.915E-04
4.00E+00	-9.916E-04
4.50E+00	-9.917E-04
5.00E+00	-9.917E-04
5.50E+00	-9.918E-04
6.00E+00	-9.919E-04
6.50E+00	-9.920E-04
7.00E+00	-9.920E-04
7.50E+00	-9.921E-04
8.00E+00	-9.922E-04
8.50E+00	-9.923E-04
9.00E+00	-9.924E-04
9.50E+00	-9.924E-04
1.00E+01	-9.925E-04
1.05E+01	-9.926E-04
1.10E+01	-9.927E-04
1.15E+01	-9.927E-04
1.20E+01	-9.928E-04
1.25E+01	-9.929E-04
1.30E+01	-9.929E-04
1.35E+01	-9.930E-04
1.40E+01	-9.931E-04
1.45E+01	-9.932E-04
1.50E+01	-9.932E-04

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:2	= 1.353E+00	0:3	= 6.765E-01	0:4	= 2.000E+00
+0:100	= 1.500E+01				

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT			
ELEMENT	0:Q1	0:Q2	0:Q3
MODEL	0:NPN	0:NPN	0:NPN
IB	9.811E-06	9.863E-06	9.815E-06
IC	9.863E-04	9.913E-04	9.815E-04
VBE	6.765E-01	6.766E-01	6.765E-01
VCE	1.353E+00	1.323E+00	6.765E-01
VBC	-6.766E-01	-6.469E-01	0.
VS	-1.353E+00	-2.000E+00	-6.765E-01
POWER	1.341E-03	1.319E-03	6.706E-04
BETAD	1.005E+02	1.005E+02	1.000E+02
GM	3.812E-02	3.832E-02	3.794E-02
RPI	2.636E+03	2.622E+03	2.635E+03
RX	2.000E+02	2.000E+02	2.000E+02
RO	1.325E+05	1.318E+05	1.324E+05
BETAAC	1.005E+02	1.004E+02	9.998E+01

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(2)/VO = -2.055E-04
 INPUT RESISTANCE AT VO = 6.039E+06
 OUTPUT RESISTANCE AT V(2) = 5.963E+01

4-10

$$g_{01} = \frac{I_{REF}}{L_{eff}} \frac{dX_d}{dV_{DS}} = \frac{I_{REF}}{0.82} (0.02)$$

$$= 0.024 I_{REF}$$

$$g_{02} = \frac{I_{REF}}{0.82} (0.04) = 0.049 I_{REF}$$

 $I_{REF} (\mu A)$

1000

100

10

1

 A_V (hand calc.)

-95

-300

-350

-350

① In strong inversion,

$$g_{m1} = \sqrt{2 K' \left(\frac{W}{L_{eff}} \right) I_{REF}}$$

$$= \sqrt{2 \times 1.94 \times 10^{-4} \times \frac{100}{0.82} I_{REF}}$$

$$= 0.22 \sqrt{I_{REF}}$$

$$A_V = \frac{-g_{m1}}{g_{01} + g_{02}} = \frac{-0.22 \sqrt{I_{REF}}}{0.073 I_{REF}}$$

$$= \frac{-3.0}{\sqrt{I_{REF}}}$$

 $I_{REF} (\mu A)$

1000

100

10

1

 A_V (hand calc.)

-95

-300

-950

-3000

② In the last two cases above,

$$(V_{GS} - V_t)_1 \text{ calculated by } \sqrt{\frac{2 I_{REF}}{K' W/L_{eff}}} < 78 \text{ mV}$$

Therefore, M_1 operates in weak inversion for these cases

$$\text{From (1.253), } g_{m1} = \frac{I_{REF}}{n V_T} = \frac{I_{REF}}{(1.5)(26 \text{ mV})}$$

$$A_V = \frac{-g_{m1}}{g_{01} + g_{02}} = \frac{-I_{REF}}{(1.5)(26 \text{ mV})} \frac{1}{0.073 I_{REF}}$$

$$= -350$$

COMMON-SOURCE AMP WITH COMPLEMENTARY LOAD

* WITH IR = 1 MA AND WITHOUT WEAK INVERSION EFFECTS

VDD 100 0 3

VI 1 0 893.3M AC 1

*THE DC INPUT IS ADJUSTED BY TRIAL AND ERROR SO THAT THE

*DC OUTPUT VOLTAGE IS ABOUT 1 VOLT.

M1 2 1 0 0 CMOSN W=100U L=1U

M2 2 3 100 100 CMOSP W=100U L=1U

M3 3 3 100 100 CMOSP W=100U L=1U

IR 3 0 1M

.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0.024 VTO=0.6 KP=194U LD=0.09U

.MODEL CMOSP PMOS LEVEL=1 LAMBDA=0.049 VTO=-0.6 KP=65U LD=0.09U

.OPTIONS NOMOD NOPAGE

.WIDTH OUT=80

.OP

.TF V(2) VI

.END

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:1	= 8.933E-01	0:2	= 1.004E+00	0:3	= 1.910E+00
+0:100	= 3.000E+00				

**** MOSFETS

SUBCKT

ELEMENT	0:M1	0:M2	0:M3
MODEL	0:CMOSN	0:CMOSP	0:CMOSP
ID	1.042E-03	-1.042E-03	-1.000E-03
IBS	0.	0.	0.
IBD	-1.005E-14	1.995E-14	1.089E-14
VGS	8.933E-01	-1.089E+00	-1.089E+00
VDS	1.004E+00	-1.995E+00	-1.089E+00
VBS	0.	0.	0.
VTH	6.000E-01	-6.000E-01	-6.000E-01
VDSAT	2.933E-01	-4.894E-01	-4.894E-01
BETA	2.423E-02	8.702E-03	8.350E-03
GAM EFF	0.	0.	0.
GM	7.106E-03	4.259E-03	4.087E-03
GDS	2.442E-05	4.652E-05	4.652E-05
GMB	0.	0.	0.

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(2)/VI	= -1.001E+02
INPUT RESISTANCE AT VI	= 1.000E+20
OUTPUT RESISTANCE AT V(2)	= 1.409E+04

COMMON-SOURCE AMP WITH COMPLEMENTARY LOAD

* WITH IR = 100 UA AND WITHOUT WEAK INVERSION EFFECTS

VDD 100 0 3

VI 1 0 693.4M AC 1

*THE DC INPUT IS ADJUSTED BY TRIAL AND ERROR SO THAT THE

*DC OUTPUT VOLTAGE IS ABOUT 1 VOLT.

M1 2 1 0 0 CMOSN W=100U L=1U

M2 2 3 100 100 CMOSP W=100U L=1U

M3 3 3 100 100 CMOSP W=100U L=1U

IR 3 0 100U

.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0.024 VTO=0.6 KP=194U LD=0.09U

.MODEL CMOSP PMOS LEVEL=1 LAMBDA=0.049 VTO=-0.6 KP=65U LD=0.09U

.OPTIONS NOMOD NOPAGE

.WIDTH OUT=80

.OP

.TF V(2) VI

.END

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:1	= 6.934E-01	0:2	= 1.028E+00	0:3	= 2.244E+00
+0:100	= 3.000E+00				

**** MOSFETS

SUBCKT

ELEMENT	0:M1	0:M2	0:M3
MODEL	0:CMOSN	0:CMOSP	0:CMOSP
ID	1.057E-04	-1.057E-04	-1.000E-04
IBS	0.	0.	0.
IBD	-1.029E-14	1.971E-14	7.560E-15
VGS	6.934E-01	-7.560E-01	-7.560E-01
VDS	1.028E+00	-1.971E+00	-7.560E-01
VBS	0.	0.	0.
VTH	6.000E-01	-6.000E-01	-6.000E-01
VDSAT	9.340E-02	-1.560E-01	-1.560E-01
BETA	2.424E-02	8.692E-03	8.220E-03
GAM EFF	0.	0.	0.
GM	2.264E-03	1.356E-03	1.282E-03
GDS	2.477E-06	4.725E-06	4.725E-06
GMB	0.	0.	0.

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(2)/VI	= -3.144E+02
INPUT RESISTANCE AT VI	= 1.000E+20
OUTPUT RESISTANCE AT V(2)	= 1.388E+05

COMMON-SOURCE AMP WITH COMPLEMENTARY LOAD

* WITH IR = 10 UA AND WITHOUT WEAK INVERSION EFFECTS

VDD 100 0 3

VI 1 0 629.6M AC 1

*THE DC INPUT IS ADJUSTED BY TRIAL AND ERROR SO THAT THE

*DC OUTPUT VOLTAGE IS ABOUT 1 VOLT.

M1 2 1 0 0 CMOSN W=100U L=1U

M2 2 3 100 100 CMOSP W=100U L=1U

M3 3 3 100 100 CMOSP W=100U L=1U

IR 3 0 10U

.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0.024 VTO=0.6 KP=194U LD=0.09U

.MODEL CMOSP PMOS LEVEL=1 LAMBDA=0.049 VTO=-0.6 KP=65U LD=0.09U

.OPTIONS NOMOD NOPAGE

.WIDTH OUT=80

.OP

.TF V(2) VI

.END

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:1	= 6.296E-01	0:2	= 1.039E+00	0:3	= 2.350E+00
+0:100	= 3.000E+00				

**** MOSFETS

SUBCKT

ELEMENT	0:M1	0:M2	0:M3
MODEL	0:CMOSN	0:CMOSP	0:CMOSP
ID	1.062E-05	-1.062E-05	-1.000E-05
IBS	0.	0.	0.
IBD	-1.039E-14	1.961E-14	6.494E-15
VGS	6.296E-01	-6.494E-01	-6.494E-01
VDS	1.039E+00	-1.960E+00	-6.494E-01
VBS	0.	0.	0.
VTH	6.000E-01	-6.000E-01	-6.000E-01
VDSAT	2.960E-02	-4.945E-02	-4.945E-02
BETA	2.425E-02	8.688E-03	8.179E-03
GAM EFF	0.	0.	0.
GM	7.178E-04	4.296E-04	4.045E-04
GDS	2.487E-07	4.749E-07	4.749E-07
GMB	0.	0.	0.

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(2)/VI	= -9.918E+02
INPUT RESISTANCE AT VI	= 1.000E+20
OUTPUT RESISTANCE AT V(2)	= 1.381E+06

COMMON-SOURCE AMP WITH COMPLEMENTARY LOAD

* WITH IR = 1 UA AND WITHOUT WEAK INVERSION EFFECTS

VDD 100 0 3

VI 1 0 609.38M AC 1

*THE DC INPUT IS ADJUSTED BY TRIAL AND ERROR SO THAT THE

*DC OUTPUT VOLTAGE IS ABOUT 1 VOLT.

M1 2 1 0 0 CMOSN W=100U L=1U

M2 2 3 100 100 CMOSP W=100U L=1U

M3 3 3 100 100 CMOSP W=100U L=1U

IR 3 0 1U

.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0.024 VTO=0.6 KP=194U LD=0.09U

.MODEL CMOSP PMOS LEVEL=1 LAMBDA=0.049 VTO=-0.6 KP=65U LD=0.09U

.OPTIONS NOMOD NOPAGE

.WIDTH OUT=80

.OP

.TF V(2) VI

.END

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:1	= 6.094E-01 0:2	= 1.001E+00 0:3	= 2.384E+00		
+0:100	= 3.000E+00				

**** MOSFETS

SUBCKT

ELEMENT	0:M1	0:M2	0:M3
MODEL	0:CMOSN	0:CMOSP	0:CMOSP
ID	1.066E-06	-1.066E-06	-1.000E-06
IBS	0.	0.	0.
IBD	-1.001E-14	1.999E-14	6.156E-15
VGS	6.094E-01	-6.156E-01	-6.156E-01
VDS	1.001E+00	-1.998E+00	-6.156E-01
VBS	0.	0.	0.
VTH	6.000E-01	-6.000E-01	-6.000E-01
VDSAT	9.380E-03	-1.565E-02	-1.565E-02
BETA	2.423E-02	8.703E-03	8.166E-03
GAM EFF	0.	0.	0.
GM	2.272E-04	1.362E-04	1.278E-04
GDS	2.498E-08	4.757E-08	4.757E-08
GMB	0.	0.	0.

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(2)/VI	= -3.132E+03
INPUT RESISTANCE AT VI	= 1.000E+20
OUTPUT RESISTANCE AT V(2)	= 1.378E+07

COMMON-SOURCE AMP WITH COMPLEMENTARY LOAD

* WITH IR = 1 NA AND WITH WEAK INVERSION EFFECTS

VDD 100 0 3

VI 1 0 901.0M AC 1

*THE DC INPUT IS ADJUSTED BY TRIAL AND ERROR SO THAT THE

*DC OUTPUT VOLTAGE IS ABOUT 1 VOLT.

M1 2 1 0 0 CMOSN W=100U L=1U

M2 2 3 100 100 CMOSP W=100U L=1U

M3 3 3 100 100 CMOSP W=100U L=1U

IR 3 0 1M

* TO INCLUDE WEAK INVERSION EFFECTS, MUST CHANGE TO AT LEAST

* THE LEVEL 2 MODEL.

.MODEL CMOSN NMOS LEVEL=2 VTO=0.6 KP=194U LD=0.09U

+ TOX=8E-09 LAMBDA=0.024 NFS=1.35E12 NSUB=5E15

.MODEL CMOSP PMOS LEVEL=2 VTO=-0.6 KP=65U LD=0.09U

+ TOX=8E-09 LAMBDA=0.049 NFS=1.35E12 NSUB=4E16

* IN THE HSPICE MODEL, ID IS PROPORTIONAL TO $\exp[(VGS - VT)/FAST]$ * IN CHAPTER 1, ID IS PROPORTIONAL TO $\exp[(VGS - VT)/(NVT)]$

* THEREFORE, FAST MUST EQUAL NVT (WHICH IS N THERMAL VOLTAGES)

* FROM PAGE 7-19 OF THE HSPICE MANUAL,

* FAST IS ABOUT EQUAL TO $VT(1 + Q \cdot NFS/COX)$ * THEREFORE $N = 1 + Q \cdot NFS/COX$ * SOLVING FOR NFS GIVES $NFS = (N-1)COX/Q$ * COX SHOULD BE IN FARADS/CM² AND Q IS IN COULOMBS* FOR EXAMPLE, IF $N=1.5$, $COX = 4.32E-7$ (FOR TOX=80 ANGSTROMS)* $NFS = 0.5 \cdot 4.32E-7 / 1.6E-19 = 1.35E12$

.OPTIONS NOMOD NOPAGE

.WIDTH OUT=80

.OP

.TF V(2) VI

.END

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:1	= 9.010E-01 0:2	= 1.077E+00 0:3	= 1.878E+00		
+0:100	= 3.000E+00				

**** MOSFETS

SUBCKT

ELEMENT	0:M1	0:M2	0:M3
MODEL	0:CMOSN	0:CMOSP	0:CMOSP
ID	1.043E-03	-1.043E-03	-1.000E-03
IBS	0.	0.	0.
IBD	-1.078E-14	1.922E-14	1.121E-14
VGS	9.010E-01	-1.121E+00	-1.121E+00
VDS	1.077E+00	-1.922E+00	-1.121E+00
VBS	0.	0.	0.
VTH	6.000E-01	-6.000E-01	-6.000E-01
VDSAT	2.859E-01	-4.595E-01	-4.595E-01
BETA	2.429E-02	8.751E-03	8.388E-03
GAM EFF	9.438E-02	2.670E-01	2.670E-01
GM	6.943E-03	4.021E-03	3.854E-03
GDS	2.570E-05	5.644E-05	5.185E-05
GMB	3.674E-04	5.414E-04	5.189E-04

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(2)/VI	= -8.452E+01
INPUT RESISTANCE AT VI	= 1.000E+20
OUTPUT RESISTANCE AT V(2)	= 1.217E+04

COMMON-SOURCE AMP WITH COMPLEMENTARY LOAD

* WITH IR = 100 UA AND WITH WEAK INVERSION EFFECTS

VDD 100 0 3

VI 1 0 696.4M AC 1

*THE DC INPUT IS ADJUSTED BY TRIAL AND ERROR SO THAT THE

*DC OUTPUT VOLTAGE IS ABOUT 1 VOLT.

M1 2 1 0 0 CMOSN W=100U L=1U

M2 2 3 100 100 CMOSP W=100U L=1U

M3 3 3 100 100 CMOSP W=100U L=1U

IR 3 0 100U

* TO INCLUDE WEAK INVERSION EFFECTS, MUST CHANGE TO AT LEAST

* THE LEVEL 2 MODEL.

.MODEL CMOSN NMOS LEVEL=2 VTO=0.6 KP=194U LD=0.09U

+ TOX=8E-09 LAMBDA=0.024 NFS=1.35E12 NSUB=5E15

.MODEL CMOSP PMOS LEVEL=2 VTO=-0.6 KP=65U LD=0.09U

+ TOX=8E-09 LAMBDA=0.049 NFS=1.35E12 NSUB=4E16

* IN THE HSPICE MODEL, ID IS PROPORTIONAL TO $\exp[(VGS - VT)/FAST]$ * IN CHAPTER 1, ID IS PROPORTIONAL TO $\exp[(VGS - VT)/(NVT)]$

* THEREFORE, FAST MUST EQUAL NVT (WHICH IS N THERMAL VOLTAGES)

* FROM PAGE 7-19 OF THE HSPICE MANUAL,

* FAST IS ABOUT EQUAL TO $VT(1 + Q \cdot NFS/COX)$ * THEREFORE $N = 1 + Q \cdot NFS/COX$ * SOLVING FOR NFS GIVES $NFS = (N-1)COX/Q$ * COX SHOULD BE IN FARADS/CM² AND Q IS IN COULOMBS* FOR EXAMPLE, IF $N=1.5$, $COX = 4.32E-7$ (FOR TOX=80 ANGSTROMS)* $NFS = 0.5 \cdot 4.32E-7 / 1.6E-19 = 1.35E12$

.OPTIONS NOMOD NOPAGE

.WIDTH OUT=80

.OP

.TF V(2) VI

.END

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:1	= 6.964E-01 0:2	= 1.014E+00 0:3	= 2.233E+00		
+0:100	= 3.000E+00				

**** MOSFETS

SUBCKT

```

ELEMENT 0:M1      0:M2      0:M3
MODEL    0:CMOSN  0:CMOSP   0:CMOSP
ID       1.066E-04 -1.066E-04 -1.000E-04
IBS      0.        0.        0.
IBD      -1.015E-14 1.985E-14 7.670E-15
VGS      6.964E-01 -7.670E-01 -7.670E-01
VDS      1.014E+00 -1.985E+00 -7.670E-01
VBS      0.        0.        0.
VTH      6.000E-01 -6.000E-01 -6.000E-01
VDSAT    9.127E-02 -1.457E-01 -1.457E-01
BETA     2.425E-02 8.781E-03 8.236E-03
GAM EFF  9.438E-02 2.670E-01 2.670E-01
GM       2.213E-03 1.279E-03 1.200E-03
GDS      2.623E-06 5.787E-06 5.091E-06
GMB      1.245E-04 1.866E-04 1.750E-04

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(2)/VI      = -2.631E+02
INPUT RESISTANCE AT VI      = 1.000E+20
OUTPUT RESISTANCE AT V(2)   = 1.189E+05

```

COMMON-SOURCE AMP WITH COMPLEMENTARY LOAD

* WITH IR = 10 UA AND WITH WEAK INVERSION EFFECTS

VDD 100 0 3

VI 1 0 618.1M AC 1

*THE DC INPUT IS ADJUSTED BY TRIAL AND ERROR SO THAT THE

*DC OUTPUT VOLTAGE IS ABOUT 1 VOLT.

M1 2 1 0 0 CMOSN W=100U L=1U

M2 2 3 100 100 CMOSP W=100U L=1U

M3 3 3 100 100 CMOSP W=100U L=1U

IR 3 0 10U

* TO INCLUDE WEAK INVERSION EFFECTS, MUST CHANGE TO AT LEAST

* THE LEVEL 2 MODEL.

.MODEL CMOSN NMOS LEVEL=2 VTO=0.6 KP=194U LD=0.09U

+ TOX=8E-09 LAMBDA=0.024 NFS=1.35E12 NSUB=5E15

.MODEL CMOSP PMOS LEVEL=2 VTO=-0.6 KP=65U LD=0.09U

+ TOX=8E-09 LAMBDA=0.049 NFS=1.35E12 NSUB=4E16

* IN THE HSPICE MODEL, ID IS PROPORTIONAL TO EXP[(VGS - VT)/FAST]

* IN CHAPTER 1, ID IS PROPORTIONAL TO EXP[(VGS - VT)/(NVT)]

* THEREFORE, FAST MUST EQUAL NVT (WHICH IS N THERMAL VOLTAGES)

* FROM PAGE 7-19 OF THE HSPICE MANUAL,

* FAST IS ABOUT EQUAL TO VT(1 + Q NFS/COX)

* THEREFORE N = 1 + Q NFS/COX

* SOLVING FOR NFS GIVES NFS = (N-1)COX/Q

* COX SHOULD BE IN FARADS/CM^2 AND Q IS IN COULOMBS

* FOR EXAMPLE, IF N=1.5, COX = 4.32E-7 (FOR TOX=80 ANGSTROMS)

* NFS = 0.5*4.32E-7/1.6E-19 = 1.35E12

.OPTIONS NOMOD NOPAGE

.WIDTH OUT=80

.OP

.TF V(2) VI

.END

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

```

NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:1      = 6.181E-01 0:2      = 9.893E-01 0:3      = 2.347E+00
+0:100    = 3.000E+00

```

**** MOSFETS

SUBCKT

```

ELEMENT 0:M1      0:M2      0:M3
MODEL    0:CMOSN  0:CMOSP   0:CMOSP
ID       1.074E-05 -1.074E-05 -1.000E-05
IBS      0.        0.        0.
IBD      -9.893E-15 2.011E-14 6.530E-15
VGS      6.181E-01 -6.530E-01 -6.530E-01
VDS      9.893E-01 -2.010E+00 -6.530E-01
VBS      0.        0.        0.
VTH      6.000E-01 -6.000E-01 -6.000E-01
VDSAT    3.814E-02 -4.609E-02 -4.609E-02
BETA     2.423E-02 8.793E-03 8.189E-03
GAM EFF  9.438E-02 2.670E-01 2.670E-01
GM       2.663E-04 4.053E-04 3.775E-04
GDS      2.640E-07 5.837E-07 5.062E-07
GMB      1.457E-05 6.089E-05 5.671E-05

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(2)/VI      = -3.141E+02
INPUT RESISTANCE AT VI      = 9.999E+19
OUTPUT RESISTANCE AT V(2)   = 1.179E+06

```

COMMON-SOURCE AMP WITH COMPLEMENTARY LOAD

* WITH IR = 1 UA AND WITH WEAK INVERSION EFFECTS

VDD 100 0 3

VI 1 0 525.4M AC 1

*THE DC INPUT IS ADJUSTED BY TRIAL AND ERROR SO THAT THE

*DC OUTPUT VOLTAGE IS ABOUT 1 VOLT.

M1 2 1 0 0 CMOSN W=100U L=1U

M2 2 3 100 100 CMOSP W=100U L=1U

M3 3 3 100 100 CMOSP W=100U L=1U

IR 3 0 1U

* TO INCLUDE WEAK INVERSION EFFECTS, MUST CHANGE TO AT LEAST

* THE LEVEL 2 MODEL.

.MODEL CMOSN NMOS LEVEL=2 VTO=0.6 KP=194U LD=0.09U

+ TOX=8E-09 LAMBDA=0.024 NFS=1.35E12 NSUB=5E15

.MODEL CMOSP PMOS LEVEL=2 VTO=-0.6 KP=65U LD=0.09U

+ TOX=8E-09 LAMBDA=0.049 NFS=1.35E12 NSUB=4E16

* IN THE HSPICE MODEL, ID IS PROPORTIONAL TO EXP[(VGS - VT)/FAST]

* IN CHAPTER 1, ID IS PROPORTIONAL TO EXP[(VGS - VT)/(NVT)]

* THEREFORE, FAST MUST EQUAL NVT (WHICH IS N THERMAL VOLTAGES)

* FROM PAGE 7-19 OF THE HSPICE MANUAL,

* FAST IS ABOUT EQUAL TO VT(1 + Q NFS/COX)

* THEREFORE N = 1 + Q NFS/COX

* SOLVING FOR NFS GIVES NFS = (N-1)COX/Q

* COX SHOULD BE IN FARADS/CM^2 AND Q IS IN COULOMBS

* FOR EXAMPLE, IF N=1.5, COX = 4.32E-7 (FOR TOX=80 ANGSTROMS)

* NFS = 0.5*4.32E-7/1.6E-19 = 1.35E12

.OPTIONS NOMOD NOPAGE

.WIDTH OUT=80

.OP

.TF V(2) VI

.END

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

```

NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:1      = 5.254E-01 0:2      = 9.969E-01 0:3      = 2.437E+00
+0:100    = 3.000E+00

```

**** MOSFETS

SUBCKT

```

ELEMENT 0:M1      0:M2      0:M3
MODEL    0:CMOSN  0:CMOSP   0:CMOSP
ID       1.078E-06 -1.078E-06 -1.000E-06
IBS      0.        0.        0.
IBD      -9.969E-15 2.003E-14 5.629E-15
VGS      5.254E-01 -5.629E-01 -5.629E-01
VDS      9.969E-01 -2.003E+00 -5.629E-01
VBS      0.        0.        0.
VTH      6.000E-01 -6.000E-01 -6.000E-01
VDSAT    3.814E-02 -3.717E-02 -3.717E-02
BETA     2.424E-02 8.790E-03 8.152E-03
GAM EFF  9.438E-02 2.670E-01 2.670E-01
GM       2.674E-05 2.521E-05 2.338E-05
GDS      2.651E-08 5.858E-08 5.039E-08
GMB      1.393E-06 3.567E-06 3.308E-06

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(2)/VI      = -3.141E+02
INPUT RESISTANCE AT VI      = 9.999E+19
OUTPUT RESISTANCE AT V(2)   = 1.175E+07

```

4.11

From (1.140),

$$V_{t2} = V_{t2,0} + \gamma \left[\sqrt{2\phi_f + V_{SB2}} - \sqrt{2\phi_f} \right]$$

$$C_{ox} = \frac{3.9 \times 8.86 \times 10^{-14}}{80 \times 10^{-8}} = 4.3 \times 10^{-7} \frac{F}{cm^2}$$

$$\gamma = \frac{1}{4.3 \times 10^{-7}} \sqrt{2(1.6 \times 10^{-19})(11.6)(8.86 \times 10^{-14})(5 \times 10^{-15})}$$

$$= 0.094 V^{1/2}$$

From (1.135),

$$2\phi_f = 2V_T \ln \frac{5 \times 10^{15}}{1.45 \times 10^{10}} = 663 \text{ mV}$$

$$\text{SO, } V_{t2} = -1 + 0.094 \left[\sqrt{1.663} - \sqrt{0.663} \right] = -0.955$$

$$I_{D2} = \frac{\kappa'}{2} \left(\frac{W}{L_{eff2}} \right) (V_{GS2} - V_{t2})^2 = \frac{194}{2} \frac{10}{0.82} (0 + 0.955)^2 = 1.08 \text{ mA}$$

From (4.120),

$$\frac{v_o}{v_i} = -g_{m1} \left(r_{o1} \parallel r_{o2} \parallel \frac{1}{g_{mb2}} \right) = \frac{-g_{m1}}{g_{o1} + g_{o2} + g_{mb2}}$$

$$g_{m1} = \sqrt{2(194) \frac{100}{0.82} (1080)} = 7.2 \text{ mA/V}$$

From (1.199),

$$g_{mb2} = \frac{\gamma \kappa' \left(\frac{W}{L_{eff}} \right) (V_{GS2} - V_{t2})}{2 \sqrt{2\phi_f + V_{SB2}}} = \frac{0.094(194) \frac{10}{0.82} (0.955)}{2 \sqrt{1.663}} = 82.3 \mu A/V$$

$$g_{o1} = g_{o2} = r_{o1}^{-1} = r_{o2}^{-1} = \frac{I_D}{L_{eff}} \frac{dX_d}{dV_{DS}} = \frac{1.08}{0.82} (0.02)$$

$$= 26.3 \mu A/V$$

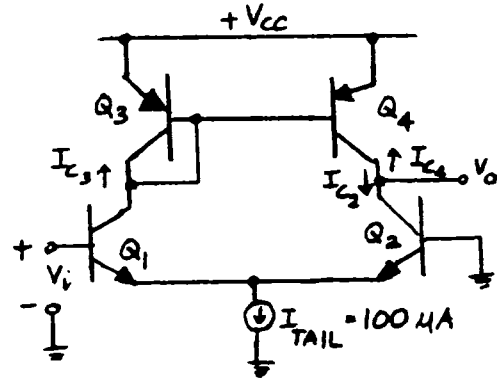
$$\frac{v_o}{v_i} = \frac{-7.2 \text{ m}}{2(26.3 \mu) + 82.3} = -53$$

4.12

$$V_{A_{PNP}} = 50 \text{ V} \quad V_{A_{NPN}} = 130 \text{ V}$$

$$\beta_{F_{PNP}} = 50 \quad \beta_{F_{NPN}} = 200$$

Assume no device mismatch



$$I_{C1} \approx I_{C2} = \frac{I_{EE}}{2} = 50 \mu A = I_C$$

$$I_{C3} \approx I_{C4} = -50 \mu A$$

$$\therefore g_m = \frac{I_C}{V_T} = \frac{50 \mu A}{26 \text{ mV}} = \frac{1}{520} \text{ V}$$

$$r_{opnp} = \frac{V_{A_{PNP}}}{I_C} = 1 \text{ M}\Omega$$

$$r_{onpn} = \frac{V_{A_{NPN}}}{I_C} = 2.6 \text{ M}\Omega$$

since unloaded, the output resistance is

$$R_{out} = r_{opnp} \parallel r_{onpn} = 722 \text{ k}\Omega$$

$$A_v = g_m R_{out} = \frac{1}{520} \times 722 \text{ k} = 1388$$

BJT DIFFERENTIAL PAIR WITH CURRENT-MIRROR LOAD

```

VCC 100 0 2.5
VEE 200 0 -2.5
Q1 2 3 4 NPN
Q2 6 0 4 NPN
Q3 2 2 100 PNP
Q4 6 2 100 PNP
ITAIL 4 200 100U
RTAIL 4 200 1MEG
.MODEL NPN NPN RB=200 BF=200 VAF=130 IS=5E-15
.MODEL PNP PNP RB=300 BF=50 VAF=50 IS=2E-15

```

* A DC INPUT VOLTAGE OF ABOUT 1 MV FORCES THE COLLECTOR-EMITTER
 * VOLTAGE OF Q2 ABOUT EQUAL TO THAT OF Q1.

```

VIDC 3 5 1M
VI 5 0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VI -0.01 0.01 0.002
.PLOT DC V(6)
.TF V(6) VI
.END

```

***** DC TRANSFER CURVES TNOM= 27.000 TEMP= 27.000

VOLT	V(6)								
1.000E-02	-5.47E-01	A+							
8.000E-03	-5.39E-01	A+							
6.000E-03	-5.29E-01	A							
4.000E-03	-5.12E-01	A							
2.000E-03	-4.63E-01	A+							
0.	1.85E+00								
2.000E-03	2.39E+00								
4.000E-03	2.41E+00								
6.000E-03	2.42E+00								
8.000E-03	2.43E+00								
1.000E-02	2.44E+00								

```

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000
NODE =VOLTAGE NODE =VOLTAGE NODE =VOLTAGE
+0:2 = 1.880E+00 0:3 = 1.000E-03 0:4 = -5.951E-01
+0:5 = 0. 0:6 = 1.857E+00 0:100 = 2.500E+00
+0:200 = -2.500E+00

```

**** BIPOLAR JUNCTION TRANSISTORS

```

SUBCKT
ELEMENT 0:Q1 0:Q2 0:Q3 0:Q4
MODEL 0:NPN 0:NPN 0:PNP 0:PNP
IB 2.547E-07 2.451E-07 -9.939E-07 -9.939E-07
IC 5.168E-05 4.972E-05 -4.970E-05 -4.972E-05
VBE 5.961E-01 5.951E-01 -6.194E-01 -6.194E-01
VCE 2.475E+00 2.452E+00 -6.194E-01 -6.426E-01
VBC -1.879E+00 -1.857E+00 0. 2.318E-02
VS -1.880E+00 -1.857E+00 -1.880E+00 -1.880E+00
POWER 1.281E-04 1.221E-04 3.140E-05 3.256E-05
BETAD 2.028E+02 2.028E+02 5.000E+01 5.002E+01
GM 1.998E-03 1.922E-03 1.920E-03 1.921E-03
RPI 1.015E+05 1.055E+05 2.602E+04 2.602E+04
RX 2.000E+02 2.000E+02 3.000E+02 3.000E+02
RO 2.551E+06 2.652E+06 1.006E+06 1.006E+06
BETAAC 2.028E+02 2.028E+02 4.997E+01 4.999E+01

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(6)/VI = 1.398E+03
INPUT RESISTANCE AT VI = 2.853E+05
OUTPUT RESISTANCE AT V(6) = 7.294E+05

```

BJT DIFFERENTIAL PAIR WITH CURRENT-MIRROR LOAD

* (COMMON-MODE INPUT)

```

VCC 100 0 2.5
VEE 200 0 -2.5
Q1 2 3 4 NPN
Q2 6 5 4 NPN
* |CMRR| = 1398/0.0002561 = 5.46E6
Q3 2 2 100 PNP
Q4 6 2 100 PNP
ITAIL 4 200 100U
RTAIL 4 200 1MEG
.MODEL NPN NPN RB=200 BF=200 VAF=130 IS=5E-15
.MODEL PNP PNP RB=300 BF=50 VAF=50 IS=2E-15

```

* A DC INPUT VOLTAGE OF ABOUT 1 MV FORCES THE COLLECTOR-EMITTER
 * VOLTAGE OF Q2 ABOUT EQUAL TO THAT OF Q1.

```

VIDC 3 5 1M
VI 5 0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VI -0.01 0.01 0.002
.PLOT DC V(6)
.TF V(6) VI
.END

```

***** DC TRANSFER CURVES TNOM= 27.000 TEMP= 27.000

VOLT	V(6)								
1.000E-02	1.85E+00								
8.000E-03	1.85E+00								
6.000E-03	1.85E+00								
4.000E-03	1.85E+00								
2.000E-03	1.85E+00								
0.	1.85E+00								
2.000E-03	1.85E+00								
4.000E-03	1.85E+00								
6.000E-03	1.85E+00								
8.000E-03	1.85E+00								
1.000E-02	1.85E+00								

```

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000
NODE =VOLTAGE NODE =VOLTAGE NODE =VOLTAGE
+0:2 = 1.880E+00 0:3 = 1.000E-03 0:4 = -5.951E-01
+0:5 = 0. 0:6 = 1.857E+00 0:100 = 2.500E+00
+0:200 = -2.500E+00

```

**** BIPOLAR JUNCTION TRANSISTORS

```

SUBCKT
ELEMENT 0:Q1 0:Q2 0:Q3 0:Q4
MODEL 0:NPN 0:NPN 0:PNP 0:PNP
IB 2.547E-07 2.451E-07 -9.939E-07 -9.939E-07
IC 5.168E-05 4.972E-05 -4.970E-05 -4.972E-05
VBE 5.961E-01 5.951E-01 -6.194E-01 -6.194E-01
VCE 2.475E+00 2.452E+00 -6.194E-01 -6.426E-01
VBC -1.879E+00 -1.857E+00 0. 2.318E-02
VS -1.880E+00 -1.857E+00 -1.880E+00 -1.880E+00
POWER 1.281E-04 1.221E-04 3.140E-05 3.256E-05
BETAD 2.028E+02 2.028E+02 5.000E+01 5.002E+01
GM 1.998E-03 1.922E-03 1.920E-03 1.921E-03
RPI 1.015E+05 1.055E+05 2.602E+04 2.602E+04
RX 2.000E+02 2.000E+02 3.000E+02 3.000E+02
RO 2.551E+06 2.652E+06 1.006E+06 1.006E+06
BETAAC 2.028E+02 2.028E+02 4.997E+01 4.999E+01

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(6)/VI = -2.561E-04
INPUT RESISTANCE AT VI = 1.152E+08
OUTPUT RESISTANCE AT V(6) = 7.294E+05

```

4.13

$$R_{o_{pnp}} = r_{o_{pnp}} (1 + g_m (R_E \parallel (r_{\pi} + R_E)))$$

$$= 1 \text{ M} \left(1 + \frac{1}{520} (2 \text{ k} \parallel 50 (520) + 2 \text{ k}) \right)$$

$$= 1 \text{ M} \left(1 + \frac{1867}{520} \right)$$

$$= 4.59 \text{ M}\Omega$$

$$R_{out} = 4.59 \text{ M} \parallel R_{o_{pnp}} = 4.59 \text{ M} \parallel 2.6 \text{ M}$$

$$= 1.66 \text{ M}\Omega$$

$$A_v = g_m R_{out} = \frac{1}{520} (1.66 \text{ M}) = 3192$$

BJT DIFFERENTIAL PAIR WITH EMITTER-DEGENERATED CURRENT-MIRROR LOAD *****

```
VCC 100 0 2.5
VEE 200 0 -2.5
Q1 2 3 4 NPN
Q2 6 0 4 NPN
Q3 2 2 8 PNP
Q4 6 2 9 PNP
RE3 100 8 2K
RE4 100 9 2K
ITAIL 4 200 100U
RTAIL 4 200 1MEG
.MODEL NPN NPN RB=200 BF=200 VAF=130 IS=5E-15
.MODEL PNP PNP RB=300 BF=50 VAF=50 IS=2E-15
```

* A DC INPUT VOLTAGE OF ABOUT 1 MV IS REQUIRED TO FORCE
* ALL THE TRANSISTORS TO OPERATE IN THE FORWARD-ACTIVE REGION.

```
VIDC 3 5 1M
VI 5 0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VI -0.01 0.01 0.001
.PLOT DC V(6)
.TF V(6) VI
.END
```

***** DC TRANSFER CURVES TNOM= 27.000 TEMP= 27.000

VOLT	V(6)
1.000E-02	-5.50E-01
9.000E-03	-5.46E-01
8.000E-03	-5.43E-01
7.000E-03	-5.39E-01
6.000E-03	-5.34E-01
5.000E-03	-5.28E-01
4.000E-03	-5.21E-01
3.000E-03	-5.11E-01
2.000E-03	-4.96E-01
1.000E-03	-4.58E-01
0.	1.72E+00
1.000E-03	2.28E+00
2.000E-03	2.30E+00
3.000E-03	2.31E+00
4.000E-03	2.32E+00
5.000E-03	2.33E+00
6.000E-03	2.33E+00
7.000E-03	2.34E+00
8.000E-03	2.34E+00
9.000E-03	2.34E+00
1.000E-02	2.35E+00

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE
+0:2	= 1.779E+00	0:3	= 1.000E-03	0:4	= -5.951E-01
+0:5	= 0.	0:6	= 1.727E+00	0:8	= 2.398E+00
+0:9	= 2.398E+00	0:100	= 2.500E+00	0:200	= -2.500E+00

**** BIPOLAR JUNCTION TRANSISTORS

```
SUBCKT
ELEMENT 0:Q1 0:Q2 0:Q3 0:Q4
MODEL 0:NPN 0:NPN 0:PNP 0:PNP
IB 2.550E-07 2.453E-07 -9.941E-07 -9.932E-07
IC 5.169E-05 4.971E-05 -4.970E-05 -4.971E-05
VBE 5.961E-01 5.951E-01 -6.194E-01 -6.194E-01
VCE 2.374E+00 2.322E+00 -6.194E-01 -6.713E-01
VBC -1.778E+00 -1.727E+00 0. 5.197E-02
VS -1.779E+00 -1.727E+00 -1.779E+00 -1.779E+00
POWER 1.229E-04 1.156E-04 3.140E-05 3.399E-05
BETAD 2.027E+02 2.026E+02 5.000E+01 5.005E+01
GM 1.998E-03 1.922E-03 1.921E-03 1.921E-03
RPI 1.014E+05 1.054E+05 2.601E+04 2.604E+04
RX 2.000E+02 2.000E+02 3.000E+02 3.000E+02
RO 2.549E+06 2.649E+06 1.006E+06 1.006E+06
BETAAC 2.027E+02 2.026E+02 4.997E+01 5.002E+01
```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```
V(6)/VI = 3.136E+03
INPUT RESISTANCE AT VI = 5.358E+05
OUTPUT RESISTANCE AT V(6) = 1.636E+06
```

BJT DIFFERENTIAL PAIR WITH EMITTER-DEGENERATED CURRENT-MIRROR LOAD * (COMMON-MODE INPUT) *****

```
VCC 100 0 2.5
VEE 200 0 -2.5
Q1 2 3 4 NPN
Q2 6 5 4 NPN
* |CMRR| = 3136/0.00124 = 2.53E6
Q3 2 2 8 PNP
Q4 6 2 9 PNP
RE3 100 8 2K
RE4 100 9 2K
ITAIL 4 200 100U
RTAIL 4 200 1MEG
.MODEL NPN NPN RB=200 BF=200 VAF=130 IS=5E-15
.MODEL PNP PNP RB=300 BF=50 VAF=50 IS=2E-15
```

* A DC INPUT VOLTAGE OF ABOUT 1 MV IS REQUIRED TO FORCE
* ALL THE TRANSISTORS TO OPERATE IN THE FORWARD-ACTIVE REGION.

```
VIDC 3 5 1M
VI 5 0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VI -0.01 0.01 0.001
.PLOT DC V(6)
.TF V(6) VI
.END
```

***** DC TRANSFER CURVES TNOM= 27.000 TEMP= 27.000

VOLT	V(6)
1.000E-02	1.72E+00
9.000E-03	1.72E+00
8.000E-03	1.72E+00
7.000E-03	1.72E+00
6.000E-03	1.72E+00
5.000E-03	1.72E+00
4.000E-03	1.72E+00
3.000E-03	1.72E+00
2.000E-03	1.72E+00
1.000E-03	1.72E+00
0.	1.72E+00
1.000E-03	1.72E+00
2.000E-03	1.72E+00
3.000E-03	1.72E+00
4.000E-03	1.72E+00
5.000E-03	1.72E+00
6.000E-03	1.72E+00
7.000E-03	1.72E+00
8.000E-03	1.72E+00
9.000E-03	1.72E+00
1.000E-02	1.72E+00

**** BIPOLAR JUNCTION TRANSISTORS

```
SUBCKT
ELEMENT 0:Q1 0:Q2 0:Q3 0:Q4
MODEL 0:NPN 0:NPN 0:PNP 0:PNP
IB 2.550E-07 2.453E-07 -9.941E-07 -9.932E-07
IC 5.169E-05 4.971E-05 -4.970E-05 -4.971E-05
VBE 5.961E-01 5.951E-01 -6.194E-01 -6.194E-01
VCE 2.374E+00 2.322E+00 -6.194E-01 -6.713E-01
VBC -1.778E+00 -1.727E+00 0. 5.197E-02
VS -1.779E+00 -1.727E+00 -1.779E+00 -1.779E+00
POWER 1.229E-04 1.156E-04 3.140E-05 3.399E-05
BETAD 2.027E+02 2.026E+02 5.000E+01 5.005E+01
GM 1.998E-03 1.922E-03 1.921E-03 1.921E-03
RPI 1.014E+05 1.054E+05 2.601E+04 2.604E+04
RX 2.000E+02 2.000E+02 3.000E+02 3.000E+02
RO 2.549E+06 2.649E+06 1.006E+06 1.006E+06
BETAAC 2.027E+02 2.026E+02 4.997E+01 5.002E+01
```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```
V(6)/VI = -1.240E-03
INPUT RESISTANCE AT VI = 1.150E+08
OUTPUT RESISTANCE AT V(6) = 1.636E+06
```

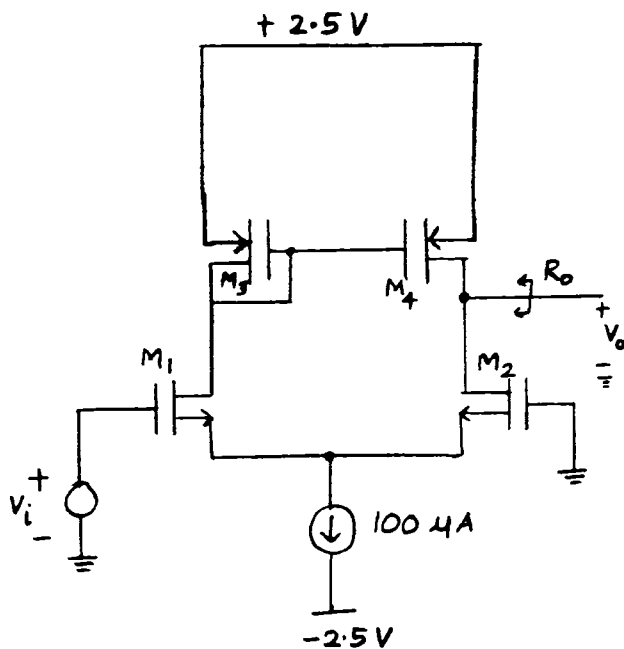
4.14

In the figure below,

$$I_1 = I_2 = I_3 = I_4 = 50 \mu\text{A}$$

and

$$R_o = r_{o2} \parallel r_{o4}$$



From (1.163),

$$V_{An} = L_{eff} / \frac{dx_d}{dV_{DS}}$$

$$\Rightarrow V_{An} = \frac{1 - 2(0.12)}{0.08} =$$

$$|V_{Ap}| = \frac{1 - 2(0.18)}{0.04} = 16 \text{ V}$$

$$r_{o2} = \frac{9.5 \text{ V}}{50 \mu\text{A}} = 190 \text{ k}\Omega$$

$$r_{o4} = \frac{16 \text{ V}}{50 \mu\text{A}} = 320 \text{ k}\Omega$$

$$C_{ox} = \frac{3.9 \times 8.854 \times 10^{-14}}{150 \times 10^{-8} \text{ cm}} = 2.3 \times 10^{-7} \frac{\text{F}}{\text{cm}^2}$$

$$K_p' = 2.3 \times 10^{-7} (250) = 58 \frac{\mu\text{A}}{\text{V}^2}$$

$$K_n' = 2.3 \times 10^{-7} (550) = 127 \frac{\mu\text{A}}{\text{V}^2}$$

$$g_{m1} = \sqrt{2 K_n' \left(\frac{W}{L}\right)_1 I_1}$$

$$= \sqrt{2(127) \frac{50}{[1 - 2(0.12)]} 50}$$

$$= 914 \frac{\mu\text{A}}{\text{V}} = G_m$$

$$R_o = r_{o2} \parallel r_{o4} = 190 \text{ k}\Omega \parallel 320 \text{ k}\Omega$$

$$= 119 \text{ k}\Omega$$

$$\frac{V_o}{V_i} = + G_m R_o = 0.914 \text{ m}(119 \text{ k})$$

$$= 109$$

From SPICE (inserted at the end),

$$\frac{V_o}{V_i} = 142 \text{ and } R_o = 138 \text{ k}\Omega$$

The difference between the hand calculations and SPICE in this case stems from the fact that early voltages are small. As a result, the expressions for transconductance and output resistance should be changed.

$$r_{o2} = \frac{V_{A1} + V_{DS2}}{I_{D2}}$$

$$V_{DS2} = 0 - V_{t2} - V_{ov2}$$

$$V_{t2} = 0.7 \text{ V (ignoring body effect)}$$

$$V_{ov2} = \sqrt{\frac{2(50)}{127(50)/[1-2(0.12)]}} = 109 \text{ mV}$$

$$V_{S2} \approx -0.7 - 0.1 = -0.8 \text{ V}$$

$$\text{If } M_1 = M_2 \text{ and } M_3 = M_4,$$

$$V_{D2} = V_{D3} = 2.5 - |V_{tp}| - |V_{ov3}|$$

$$V_{tp} = -0.7 \text{ V}$$

$$|V_{ov3}| = \sqrt{\frac{2(50)}{58(100)/[1-2(0.18)]}} = 105 \text{ mV}$$

$$V_{D2} \approx 2.5 - 0.7 - 0.1 = 1.7 \text{ V}$$

$$V_{DS2} = 1.7 + 0.8 = 2.5 \text{ V}$$

$$r_{o2} = \frac{9.5 + 2.5}{50 \mu\text{A}} = 240 \text{ k}\Omega$$

Similarly,

$$r_{o4} = \frac{|V_{Ap}| + |V_{DS4}|}{I_{D4}}$$

$$V_{DS4} = V_{DS3} = V_{GS3} \approx -0.7 - 0.1 = -0.8 \text{ V}$$

$$r_{o4} = \frac{(16 + 0.8) \text{ V}}{50 \mu\text{A}} = 336 \text{ k}\Omega$$

From (1.179),

$$g_m = \kappa' \frac{W}{L} (V_{GS} - V_t) (1 + \lambda V_{DS})$$

From (1.165)

$$I_D = \frac{\kappa'}{2} \frac{W}{L} (V_{GS} - V_t)^2 (1 + \lambda V_{DS})$$

$$\text{So, } V_{GS} - V_t = \sqrt{\frac{2I_D}{\kappa' \frac{W}{L} (1 + \lambda V_{DS})}}$$

$$\text{Then, } g_m = \kappa' \frac{W}{L} \sqrt{\frac{2I_D}{\kappa' \frac{W}{L} (1 + \lambda V_{DS})}} (1 + \lambda V_{DS})$$

$$g_m = \sqrt{2 \kappa' \frac{W}{L} I_D (1 + \lambda V_{DS})}$$

$$= \sqrt{2(127) \frac{50}{1-2(0.12)} (50) \left(1 + \frac{2.5}{9.5}\right)}$$

$$= 1027.32 \mu\text{A/V}$$

$$\frac{V_o}{V_i} = \left(1.03 \frac{\text{mA}}{\text{V}}\right) (240 \text{ k}\Omega \parallel 336 \text{ k}\Omega)$$

$$= 144.2$$

Although these final hand calculations are more accurate than the original hand calculations, hand calculations usually use the original formulae for simplicity.

MOS DIFFERENTIAL PAIR WITH CURRENT-MIRROR LOAD

```
*****
VDD 100 0 2.5
VSS 200 0 -2.5
M1 2 3 4 200 NMOS W=50U L=1U
M2 6 0 4 200 NMOS W=50U L=1U
M3 2 2 100 100 PMOS W=100U L=1U
M4 6 2 100 100 PMOS W=100U L=1U
ITAIL 4 200 100U
RTAIL 4 200 1MEG
*FOR N-CHAN, KP = UN*COX = 550*1.38E-7 = 127 UA/V**2
*FOR P-CHAN, KP = UP*COX = 250*1.38E-7 = 58 UA/V**2
.MODEL NMOS NMOS LEVEL=1 LAMBDA=0.105263 VTO=0.7 KP=127U LD=0.12U
.MODEL PMOS PMOS LEVEL=1 LAMBDA=0.0625 VTO=-0.7 KP=58U LD=0.18U
```

```
VIDC 3 5 0M
VI 5 0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VI -0.01 0.01 0.002
.PLOT DC V(6)
.TF V(6) VI
.END
```

***** DC TRANSFER CURVES TNOM= 27.000 TEMP= 27.000

VOLT	V(6)	1.000E+00	2.000E+00	3.000E+00	4.000E+00
-1.000E-02	3.41E-01	+	+	+	+
-8.000E-03	6.01E-01	+	+	+	+
-6.000E-03	8.67E-01	+	+	+	+
-4.000E-03	1.13E+00	+	+	+	+
-2.000E-03	1.41E+00	+	+	+	+
0.	1.69E+00	+	+	+	+
2.000E-03	1.98E+00	+	+	+	+
4.000E-03	2.27E+00	+	+	+	+
6.000E-03	2.41E+00	+	+	+	+
8.000E-03	2.42E+00	+	+	+	+
1.000E-02	2.42E+00	+	+	+	+

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

MODE	=VOLTAGE	MODE	=VOLTAGE	MODE	=VOLTAGE
+0:2	= 1.696E+00 0:3	= 0.	0:4	= -7.982E-01	
+0:5	= 0.	0:6	= 1.696E+00 0:100	= 2.500E+00	
+0:200	= -2.500E+00				

**** MOSFETS

```
SUBCKT
ELEMENT 0:M1 0:M2 0:M3 0:M4
MODEL 0:NMOS 0:NMOS 0:PMOS 0:PMOS
ID 5.085E-05 5.085E-05 -5.085E-05 -5.085E-05
IBS -1.702E-14 -1.702E-14 0. 0.
IBD -4.197E-14 -4.197E-14 8.034E-15 8.034E-15
VGS 7.982E-01 7.982E-01 -8.034E-01 -8.034E-01
VDS 2.494E+00 2.494E+00 -8.034E-01 -8.034E-01
VBS -1.701E+00 -1.701E+00 0. 0.
VTH 7.000E-01 7.000E-01 -7.000E-01 -7.000E-01
VDSAT 9.819E-02 9.819E-02 -1.034E-01 -1.034E-01
BETA 1.055E-02 1.055E-02 9.518E-03 9.518E-03
GAM EFF 0. 0. 0. 0.
GM 1.036E-03 1.036E-03 9.838E-04 9.838E-04
GDS 4.239E-06 4.239E-06 3.026E-06 3.026E-06
GMB 0. 0. 0. 0.
```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```
V(6)/VI = 1.423E+02
INPUT RESISTANCE AT VI = 1.000E+20
OUTPUT RESISTANCE AT V(6) = 1.379E+05
```

MOS DIFFERENTIAL PAIR WITH CURRENT-MIRROR LOAD

* (COMMON-MODE INPUT)

```
*****
VDD 100 0 2.5
VSS 200 0 -2.5
M1 2 3 4 200 NMOS W=50U L=1U
M2 6 5 4 200 NMOS W=50U L=1U
*|CMRR| = 142.3/0.0005043 = 2.82E5
M3 2 2 100 100 PMOS W=100U L=1U
M4 6 2 100 100 PMOS W=100U L=1U
ITAIL 4 200 100U
RTAIL 4 200 1MEG
*FOR N-CHAN, KP = UN*COX = 550*1.38E-7 = 127 UA/V**2
*FOR P-CHAN, KP = UP*COX = 250*1.38E-7 = 58 UA/V**2
.MODEL NMOS NMOS LEVEL=1 LAMBDA=0.105263 VTO=0.7 KP=127U LD=0.12U
.MODEL PMOS PMOS LEVEL=1 LAMBDA=0.0625 VTO=-0.7 KP=58U LD=0.18U
```

```
VIDC 3 5 0M
VI 5 0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VI -0.01 0.01 0.002
.PLOT DC V(6)
.TF V(6) VI
.END
```

***** DC TRANSFER CURVES TNOM= 27.000 TEMP= 27.000

VOLT	V(6)	1.696E+00	1.696E+00	1.696E+00	1.696E+00	1.696E+00
-1.000E-02	1.69E+00	+	+	+	+	+
-8.000E-03	1.69E+00	+	+	+	+	+
-6.000E-03	1.69E+00	+	+	+	+	+
-4.000E-03	1.69E+00	+	+	+	+	+
-2.000E-03	1.69E+00	+	+	+	+	+
0.	1.69E+00	+	+	+	+	+
2.000E-03	1.69E+00	+	+	+	+	+
4.000E-03	1.69E+00	+	+	+	+	+
6.000E-03	1.69E+00	+	+	+	+	+
8.000E-03	1.69E+00	+	+	+	+	+
1.000E-02	1.69E+00	+	+	+	+	+

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

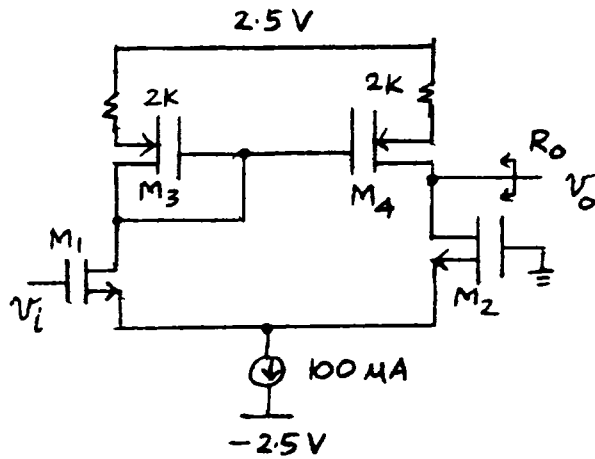
MODE	=VOLTAGE	MODE	=VOLTAGE	MODE	=VOLTAGE
+0:2	= 1.696E+00 0:3	= 0.	0:4	= -7.982E-01	
+0:5	= 0.	0:6	= 1.696E+00 0:100	= 2.500E+00	
+0:200	= -2.500E+00				

**** MOSFETS

```
SUBCKT
ELEMENT 0:M1 0:M2 0:M3 0:M4
MODEL 0:NMOS 0:NMOS 0:PMOS 0:PMOS
ID 5.085E-05 5.085E-05 -5.085E-05 -5.085E-05
IBS -1.702E-14 -1.702E-14 0. 0.
IBD -4.197E-14 -4.197E-14 8.034E-15 8.034E-15
VGS 7.982E-01 7.982E-01 -8.034E-01 -8.034E-01
VDS 2.494E+00 2.494E+00 -8.034E-01 -8.034E-01
VBS -1.701E+00 -1.701E+00 0. 0.
VTH 7.000E-01 7.000E-01 -7.000E-01 -7.000E-01
VDSAT 9.819E-02 9.819E-02 -1.034E-01 -1.034E-01
BETA 1.055E-02 1.055E-02 9.518E-03 9.518E-03
GAM EFF 0. 0. 0. 0.
GM 1.036E-03 1.036E-03 9.838E-04 9.838E-04
GDS 4.239E-06 4.239E-06 3.026E-06 3.026E-06
GMB 0. 0. 0. 0.
```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```
V(6)/VI = -5.043E-04
INPUT RESISTANCE AT VI = 1.000E+20
OUTPUT RESISTANCE AT V(6) = 1.379E+05
```

4.15

$$k_p' = 2.3 \times 10^{-7} (250) = 58 \frac{\mu A}{V^2}$$

$$R_o = r_{o2} \parallel r_{o4} (1 + g_{m4} (2k))$$

$$g_{m4} = \sqrt{2(58) \frac{100}{1 - 2(0.18)} (50)}$$

$$= 952 \mu A/V$$

$$R_o = 190k \parallel [320k + (1 + (0.952)(2))]$$

$$= 158 k\Omega$$

$$\frac{v_o}{v_i} = G_m R_o = 0.914 (158) = 144$$

MOS DIFFERENTIAL PAIR WITH SOURCE-DEGENERATED CURRENT-MIRROR LOAD

```

VDD 100 0 2.5
VSS 200 0 -2.5
M1 2 3 4 4 NMOS W=50U L=1U
M2 6 0 4 4 NMOS W=50U L=1U
* NOTE THAT CONNECTING THE BODY TO THE SOURCE ELIMINATES
* THE BODY EFFECT.
M3 2 2 8 100 PMOS W=100U L=1U
M4 6 2 9 100 PMOS W=100U L=1U
RS3 100 8 2K
RS4 100 9 2K
ITAIL 4 200 100U
RTAIL 4 200 1MEG
*FOR N-CHAN, KP = UN*COX = 550*1.38E-7 = 127 UA/V**2
*FOR P-CHAN, KP = UP*COX = 250*1.38E-7 = 58 UA/V**2
.MODEL NMOS NMOS LEVEL=1 LAMBDA=0.105263 VTO=0.7 KP=127U LD=0.12U
.MODEL PMOS PMOS LEVEL=1 LAMBDA=0.0625 VTO=-0.7 KP= 58U LD=0.18U

```

```

VIDC 3 5 0M
VI 5 0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VI -0.01 0.01 0.002
.PLOT DC V(6)
.TF V(6) VI
.END

```

***** DC TRANSFER CURVES TNOM= 27.000 TEMP= 27.000

VOLT	V(6)
(A)	-1.000E-00 0. 1.000E-00 2.000E+00 3.000E+00
-1.000E-02	-1.79E-01 + + + + +
-8.000E-03	1.49E-01 + + A + + + +
-6.000E-03	4.90E-01 + + A + + + +
-4.000E-03	8.45E-01 + + + A + + +
-2.000E-03	1.21E+00 + + + + A + +
0.	1.59E+00 + + + + A + +
2.000E-03	1.99E+00 + + + + A + +
4.000E-03	2.31E+00 + + + + A + +
6.000E-03	2.33E+00 + + + + A + +
8.000E-03	2.34E+00 + + + + A + +
1.000E-02	2.35E+00 + + + + A + +

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:2	= 1.594E+00 0:3	= 0.	0:4	= -7.986E-01	
+0:5	= 0.	0:6	= 1.594E+00 0:8	= 2.398E+00	
+0:9	= 2.398E+00 0:100	= 2.500E+00 0:200	= -2.500E+00		

**** MOSFETS

```

SUBCKT
ELEMENT 0:M1 0:M2 0:M3 0:M4
MODEL 0:NMOS 0:NMOS 0:PMOS 0:PMOS
ID 5.085E-05 5.085E-05 -5.085E-05 -5.085E-05
IBS 0. 0. 1.017E-15 1.017E-15
IBD -2.394E-14 -2.394E-14 9.051E-15 9.051E-15
VGS 7.986E-01 7.986E-01 -8.034E-01 -8.034E-01
VDS 2.393E+00 2.393E+00 -8.034E-01 -8.034E-01
VBS 0. 0. 1.017E-01 1.017E-01
VTH 7.000E-01 7.000E-01 -7.000E-01 -7.000E-01
VDSAT 9.860E-02 9.860E-02 -1.034E-01 -1.034E-01
BETA 1.046E-02 1.046E-02 9.518E-03 9.518E-03
GAM EFF 0. 0. 0. 0.
GM 1.031E-03 1.031E-03 9.838E-04 9.838E-04
GDS 4.275E-06 4.275E-06 3.026E-06 3.026E-06
GMB 0. 0. 0. 0.

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(6)/VI = 1.945E+02
INPUT RESISTANCE AT VI = 1.000E+20
OUTPUT RESISTANCE AT V(6) = 1.901E+05

```

MOS DIFFERENTIAL PAIR WITH SOURCE-DEGENERATED CURRENT-MIRROR LOAD * (COMMON-MODE INPUT)

```

VDD 100 0 2.5
VSS 200 0 -2.5
M1 2 3 4 4 NMOS W=50U L=1U
M2 6 5 4 4 NMOS W=50U L=1U
*|CMRR| = 194.5/0.0015 = 1.30E5
* NOTE THAT CONNECTING THE BODY TO THE SOURCE ELIMINATES
* THE BODY EFFECT.
M3 2 2 8 100 PMOS W=100U L=1U
M4 6 2 9 100 PMOS W=100U L=1U
RS3 100 8 2K
RS4 100 9 2K
ITAIL 4 200 100U
RTAIL 4 200 1MEG
*FOR N-CHAN, KP = UN*COX = 550*1.38E-7 = 127 UA/V**2
*FOR P-CHAN, KP = UP*COX = 250*1.38E-7 = 58 UA/V**2
.MODEL NMOS NMOS LEVEL=1 LAMBDA=0.105263 VTO=0.7 KP=127U LD=0.12U
.MODEL PMOS PMOS LEVEL=1 LAMBDA=0.0625 VTO=-0.7 KP= 58U LD=0.18U

```

```

VIDC 3 5 0M
VI 5 0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VI -0.01 0.01 0.002
.PLOT DC V(6)
.TF V(6) VI
.END

```

***** DC TRANSFER CURVES TNOM= 27.000 TEMP= 27.000

VOLT	V(6)
(A)	1.594E+00 1.594E+00 1.594E+00 1.594E+00 1.594E+00
-1.000E-02	1.59E+00 + + + + +
-8.000E-03	1.59E+00 + + + + A +
-6.000E-03	1.59E+00 + + + + A +
-4.000E-03	1.59E+00 + + + + A +
-2.000E-03	1.59E+00 + + + + A +
0.	1.59E+00 + + + + A +
2.000E-03	1.59E+00 + + + + A +
4.000E-03	1.59E+00 + + + + A +
6.000E-03	1.59E+00 + + + + A +
8.000E-03	1.59E+00 + + + + A +
1.000E-02	1.59E+00 + + + + A +

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:2	= 1.594E+00 0:3	= 0.	0:4	= -7.986E-01	
+0:5	= 0.	0:6	= 1.594E+00 0:8	= 2.398E+00	
+0:9	= 2.398E+00 0:100	= 2.500E+00 0:200	= -2.500E+00		

**** MOSFETS

```

SUBCKT
ELEMENT 0:M1 0:M2 0:M3 0:M4
MODEL 0:NMOS 0:NMOS 0:PMOS 0:PMOS
ID 5.085E-05 5.085E-05 -5.085E-05 -5.085E-05
IBS 0. 0. 1.017E-15 1.017E-15
IBD -2.394E-14 -2.394E-14 9.051E-15 9.051E-15
VGS 7.986E-01 7.986E-01 -8.034E-01 -8.034E-01
VDS 2.393E+00 2.393E+00 -8.034E-01 -8.034E-01
VBS 0. 0. 1.017E-01 1.017E-01
VTH 7.000E-01 7.000E-01 -7.000E-01 -7.000E-01
VDSAT 9.860E-02 9.860E-02 -1.034E-01 -1.034E-01
BETA 1.046E-02 1.046E-02 9.518E-03 9.518E-03
GAM EFF 0. 0. 0. 0.
GM 1.031E-03 1.031E-03 9.838E-04 9.838E-04
GDS 4.275E-06 4.275E-06 3.026E-06 3.026E-06
GMB 0. 0. 0. 0.

```

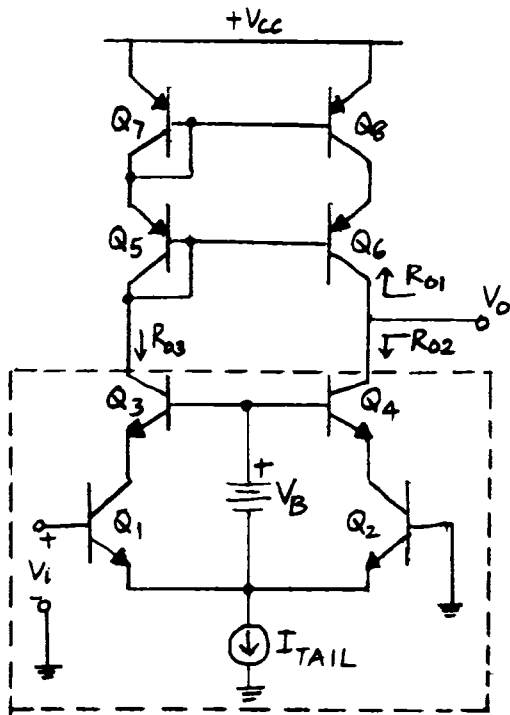
**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

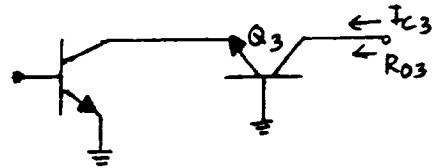
V(6)/VI = -1.500E-03
INPUT RESISTANCE AT VI = 9.999E+19
OUTPUT RESISTANCE AT V(6) = 1.901E+05

```

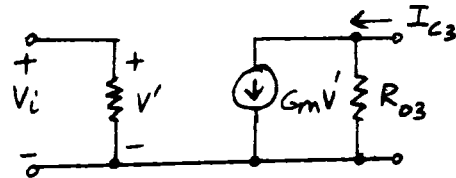
4.16



Half circuit of the dotted box :



is the CE-CB configuration.

 $\therefore$ the equivalent circuit isWhere $R_i = r_{\pi 1}$, $G_m = g_{m1}$

$$R_{O3} = \beta_3 r_{o3} = \beta_4 r_{o4} = R_{O2}$$

$$R_{OUT} = R_{O1} \parallel R_{O2}$$

$$R_{O1} \approx \frac{\beta_6 r_{o6}}{2}$$

$$I_{C1} \approx I_{C2} = I_{C3} = I_{C4} = -I_{C5} \approx -I_{C6} \\ \approx -I_{C7} = -I_{C8} \approx I_{EE}/2$$

$$\therefore g_{m1} = g_{m2} = g_{m3} = g_{m4} = g_{m5} \\ = g_{m6} = g_{m7} = g_{m8} = g_m$$

$$\beta_4 = \beta_{npn} = 200, \beta_6 = \beta_{pnp} = 50$$

$$\therefore r_{o6} = \frac{1}{g_m \eta_{pnp}}, r_{o4} = \frac{1}{g_m \eta_{npn}}$$

$$R_{OUT} = R_{O1} \parallel R_{O2}$$

$$= \frac{1}{\frac{2g_m \eta_{pnp}}{\beta_6} + \frac{g_m \eta_{npn}}{\beta_4}}$$

$$A_v = g_m R_{OUT} = \frac{1}{\frac{2 \eta_{pnp}}{\beta_6} + \frac{\eta_{npn}}{\beta_4}}$$

$$A_v = \left[\frac{1}{\left(\frac{2 \times 5 \times 10^{-4}}{50} + \frac{2 \times 10^{-4}}{200} \right)} \right] = 4.8 \times 10^4$$

BJT CASCODED DIFFERENTIAL PAIR WITH CASCODED CURRENT-MIRROR LOAD

```

VCC 100 0 2.5
VBE 200 0 -2.5
VBIAS 9 2 1.3
Q1 3 1 2 NPN
Q2 4 0 2 NPN
Q3 5 9 3 NPN
Q4 6 9 4 NPN
Q5 5 5 7 PNP
Q6 6 5 8 PNP
Q7 7 7 100 PNP
Q8 8 7 100 PNP
ITAIL 2 200 100U
RTAIL 2 200 1MEG
.MODEL NPN NPN RB=200 BF=200 VAF=130 IS=5E-15
.MODEL PNP PNP RB=300 BF=50 VAF=50 IS=2E-15

```

* A DC INPUT VOLTAGE OF ABOUT 2 MV FORCES THE VOLTAGE FROM
 * THE OUTPUT TO GROUND TO BE ABOUT EQUAL TO THE VOLTAGE
 * FROM NODE 5 (THE CASCODE CURRENT MIRROR INPUT) TO GROUND.

```

VIDC 1 10 2M
VI 10 0
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.DC VIDC -0.01 0.01 0.001
.PLOT DC V(6)
.TF V(6) VI
.END

```

***** DC TRANSFER CURVES THOM= 27.000 TEMP= 27.000

VOLT	V(6)	5.000E-01	1.000E-00	1.500E+00	2.000E+00
-1.000E-02	1.06E-01	-A			
-9.000E-03	1.11E-01	A			
-8.000E-03	1.15E-01	A			
-7.000E-03	1.20E-01	A			
-6.000E-03	1.25E-01	A			
-5.000E-03	1.31E-01	A			
-4.000E-03	1.36E-01	A			
-3.000E-03	1.43E-01	A			
-2.000E-03	1.51E-01	A			
-1.000E-03	1.60E-01	A			
0.	1.73E-01	-A			
1.000E-03	1.93E-01	A			
2.000E-03	5.86E-01	A			
3.000E-03	1.77E+00				A
4.000E-03	1.79E+00				A
5.000E-03	1.80E+00				A
6.000E-03	1.81E+00				A
7.000E-03	1.82E+00				A
8.000E-03	1.82E+00				A
9.000E-03	1.83E+00				A
1.000E-02	1.83E+00	-A			

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:1	= 2.000E-03	0:2	= -5.950E-01	0:3	= 1.081E-01
+0:4	= 1.100E-01	0:5	= 1.260E+00	0:6	= 5.857E-01
+0:7	= 1.880E+00	0:8	= 1.879E+00	0:9	= 7.050E-01
+0:10	= 0.	0:100	= 2.500E+00	0:200	= -2.500E+00

**** BIPOLAR JUNCTION TRANSISTORS

```

SUBCKT
ELEMENT 0:Q1 0:Q2 0:Q3 0:Q4
MODEL 0:NPN 0:NPN 0:NPN 0:NPN
IB 2.644E-07 2.447E-07 2.621E-07 2.439E-07
IC 5.292E-05 4.899E-05 5.265E-05 4.874E-05
VBE 5.970E-01 5.950E-01 5.968E-01 5.950E-01
VCE 7.032E-01 7.050E-01 1.152E+00 4.757E-01
VBC -1.061E-01 -1.100E-01 -5.558E-01 1.192E-01
VS -1.081E-01 -1.100E-01 -1.260E+00 -5.857E-01
POWER 3.737E-05 3.468E-05 6.084E-05 2.333E-05
BETAD 2.001E+02 2.001E+02 2.008E+02 1.998E+02
GM 2.045E-03 1.894E-03 2.035E-03 1.884E-03
RPI 9.783E+04 1.056E+05 9.866E+04 1.060E+05
RX 2.000E+02 2.000E+02 2.000E+02 2.000E+02
RO 2.458E+06 2.656E+06 2.479E+06 2.664E+06
BETAAC 2.001E+02 2.001E+02 2.008E+02 1.997E+02

```

```

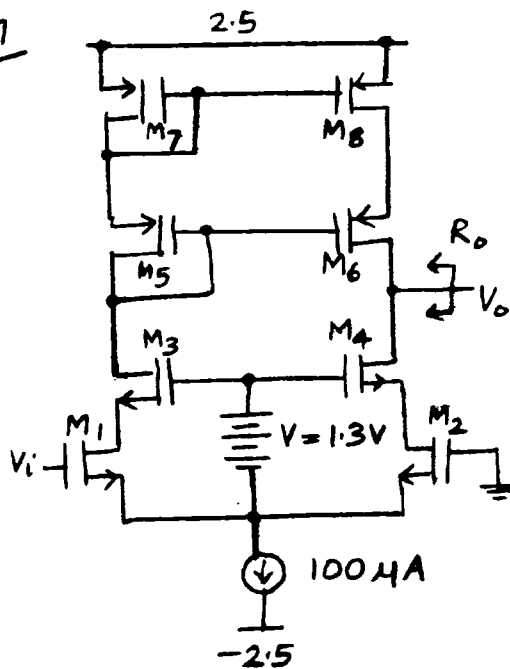
SUBCKT
ELEMENT 0:Q5 0:Q6 0:Q7 0:Q8
MODEL 0:PNP 0:PNP 0:PNP 0:PNP
IB -1.014E-06 -9.619E-07 -9.941E-07 -9.941E-07
IC -5.068E-05 -4.874E-05 -4.970E-05 -4.970E-05
VBE -6.199E-01 -6.185E-01 -6.194E-01 -6.194E-01
VCE -6.199E-01 -1.293E+00 -6.194E-01 -6.208E-01
VBC 0. 6.750E-01 0. 1.369E-03
VS -1.261E+00 -1.261E+00 -1.880E+00 -1.880E+00
POWER 3.204E-05 6.364E-05 3.140E-05 3.147E-05
BETAD 5.000E+01 5.067E+01 5.000E+01 5.000E+01
GM 1.958E-03 1.884E-03 1.921E-03 1.921E-03
RPI 2.551E+04 2.689E+04 2.601E+04 2.601E+04
RX 3.000E+02 3.000E+02 3.000E+02 3.000E+02
RO 9.866E+05 1.039E+06 1.006E+06 1.006E+06
BETAAC 4.997E+01 5.064E+01 4.997E+01 4.997E+01

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(6)/VI			= 4.909E+04
INPUT RESISTANCE AT VI			= 2.148E+05
OUTPUT RESISTANCE AT V(6)			= 2.611E+07

4.17



$$R_o = (g_{m_6} r_{o_6} r_{o_8}) \parallel (g_{m_4} r_{o_4} r_{o_2})$$

$$g_{m_6} = \sqrt{2(58) \frac{100}{0.64} (50)} = 0.952 \frac{\text{mA}}{\text{V}}$$

$$g_{m_4} = \sqrt{2(127) \frac{50}{0.76} (50)} = 0.914 \frac{\text{mA}}{\text{V}}$$

$$r_{o_6} = r_{o_8} = \frac{16}{50\ \mu} = 320\ \text{k}\Omega$$

$$r_{o_4} = r_{o_2} = \frac{9.5}{50\ \mu} = 190\ \text{k}\Omega$$

$$R_o = [(0.952)(320)^2] \parallel [(0.914)(190)^2]$$

$$= 24.7\ \text{M}\Omega$$

$$\frac{V_o}{V_i} = G_m R_o = g_{m_1} R_o$$

$$= 0.914 (24.7 \times 10^3) = 22,600$$

[In the figure, in practice V would be adjusted so that M_1 and M_2 barely operate in the active region]

MOS CASCODED DIFFERENTIAL PAIR WITH CASCODED CURRENT-MIRROR LOAD

```

VDD 100 0 2.5
VSS 200 0 -2.5
VBIAS 9 2 1.3
M1 3 1 2 2 CMOSN W=50U L=1U
M2 4 0 2 2 CMOSN W=50U L=1U
M3 5 9 3 3 CMOSN W=50U L=1U
M4 6 9 4 4 CMOSN W=50U L=1U
M5 5 5 7 7 CMOSP W=100U L=1U
M6 6 5 8 8 CMOSP W=100U L=1U
M7 7 7 100 100 CMOSP W=100U L=1U
M8 8 7 100 100 CMOSP W=100U L=1U
ITAIL 2 200 100U
RTAIL 2 200 1MEG

```

*FOR N-CHAN, KP = UN*COX = 550*1.38E-7 = 127 UA/V**2

*FOR P-CHAN, KP = UP*COX = 250*1.38E-7 = 58 UA/V**2

.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0.105263 VTO=0.7 KP=127U LD=0.12U

.MODEL CMOSP PMOS LEVEL=1 LAMBDA=0.0625 VTO=-0.7 KP= 58U LD=0.18U

VIDC 1 10 0M

VI 10 0

.OPTIONS NOMOD NOPAGE

.WIDTH OUT=80

.OP

.DC VIDC -0.01 0.01 0.001

.PLOT DC V(6)

.TF V(6) VI

.END

SUBCKT

```

ELEMENT 0:M1 0:M2 0:M3 0:M4
MODEL 0:CMOSN 0:CMOSN 0:CMOSN 0:CMOSN
ID 5.085E-05 5.085E-05 5.085E-05 5.085E-05
IBS 0. 0. 0. 0.
IBD -4.961E-15 -4.961E-15 -1.205E-14 -1.205E-14
VGS 8.076E-01 8.076E-01 8.039E-01 8.039E-01
VDS 4.961E-01 4.961E-01 1.204E+00 1.204E+00
VBS 0. 0. 0. 0.
VTH 7.000E-01 7.000E-01 7.000E-01 7.000E-01
VDSAT 1.076E-01 1.076E-01 1.039E-01 1.039E-01
BETA 8.792E-03 8.792E-03 9.415E-03 9.415E-03
GAM EFF 0. 0. 0. 0.
GM 9.455E-04 9.455E-04 9.785E-04 9.785E-04
GDS 5.087E-06 5.087E-06 4.750E-06 4.750E-06
GMB 0. 0. 0. 0.

```

SUBCKT

```

ELEMENT 0:M5 0:M6 0:M7 0:M8
MODEL 0:CMOSP 0:CMOSP 0:CMOSP 0:CMOSP
ID -5.085E-05 -5.085E-05 -5.085E-05 -5.085E-05
IBS 0. 0. 0. 0.
IBD 8.034E-15 8.034E-15 8.034E-15 8.034E-15
VGS -8.034E-01 -8.034E-01 -8.034E-01 -8.034E-01
VDS -8.034E-01 -8.034E-01 -8.034E-01 -8.034E-01
VBS 0. 0. 0. 0.
VTH -7.000E-01 -7.000E-01 -7.000E-01 -7.000E-01
VDSAT -1.034E-01 -1.034E-01 -1.034E-01 -1.034E-01
BETA 9.518E-03 9.518E-03 9.518E-03 9.518E-03
GAM EFF 0. 0. 0. 0.
GM 9.838E-04 9.838E-04 9.838E-04 9.838E-04
GDS 3.026E-06 3.026E-06 3.026E-06 3.026E-06
GMB 0. 0. 0. 0.

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(6)/VI = 2.791E+04
INPUT RESISTANCE AT VI = 1.000E+20
OUTPUT RESISTANCE AT V(6) = 2.967E+07

```

***** DC TRANSFER CURVES TNOM= 27.000 TEMP= 27.000

```

VOLT V(6)
: A ) -1.000E-00 0. 1.000E-00 2.000E+00 3.000E+00
+ + + + +
-1.000E-02 -7.30E-01 + A + + + + + + + + +
-9.000E-03 -7.27E-01 + A + + + + + + + + +
-8.000E-03 -7.24E-01 + A + + + + + + + + +
-7.000E-03 -7.21E-01 + A + + + + + + + + +
-6.000E-03 -7.17E-01 + A + + + + + + + + +
-5.000E-03 -7.13E-01 + A + + + + + + + + +
-4.000E-03 -7.08E-01 + A + + + + + + + + +
-3.000E-03 -7.01E-01 + A + + + + + + + + +
-2.000E-03 -6.59E-01 + A + + + + + + + + +
-1.000E-03 -4.71E-01 + A + + + + + + + + +
0. 8.93E-01 + A + + + + + + + + +
1.000E-03 1.98E+00 + + + + + A + + +
2.000E-03 2.28E+00 + + + + + A + + +
3.000E-03 2.40E+00 + + + + + A + + +
4.000E-03 2.46E+00 + + + + + A + + +
5.000E-03 2.41E+00 + + + + + A + + +
6.000E-03 2.41E+00 + + + + + A + + +
7.000E-03 2.41E+00 + + + + + A + + +
8.000E-03 2.42E+00 + + + + + A + + +
9.000E-03 2.42E+00 + + + + + A + + +
1.000E-02 2.42E+00 + A + + + + +
+ + + + +

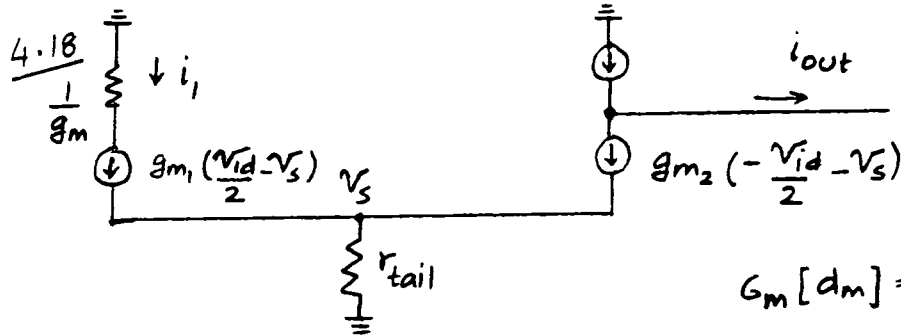
```

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

```

NODE =VOLTAGE NODE =VOLTAGE NODE =VOLTAGE
+0:1 = 0. 0:2 = -8.076E-01 0:3 = -3.115E-01
+0:4 = -3.115E-01 0:5 = 8.933E-01 0:6 = 8.933E-01
+0:7 = 1.696E+00 0:8 = 1.696E+00 0:9 = 4.924E-01
+0:10 = 0. 0:100 = 2.500E+00 0:200 = -2.500E+00

```

$$i_1 = g_{m1} \left(\frac{V_{id}}{2} - V_s \right)$$

$$i_2 = g_{m2} \left(-\frac{V_{id}}{2} - V_s \right)$$

$$V_s = (i_1 + i_2) r_{tail}$$

$$= \left[g_{m1} \left(\frac{V_{id}}{2} - V_s \right) + g_{m2} \left(-\frac{V_{id}}{2} - V_s \right) \right] r_{tail}$$

$$= \left[(g_{m1} - g_{m2}) \frac{V_{id}}{2} - (g_{m1} + g_{m2}) V_s \right] r_{tail}$$

$$\textcircled{1} V_s \left[1 + (g_{m1} + g_{m2}) r_{tail} \right] = (g_{m1} - g_{m2}) r_{tail} \frac{V_{id}}{2}$$

$$i_{out} = \frac{g_{m4}}{g_{m3}} (i_1) - i_2$$

$$= \frac{g_{m4}}{g_{m3}} g_{m1} \left(\frac{V_{id}}{2} - V_s \right) - g_{m2} \left(-\frac{V_{id}}{2} - V_s \right)$$

$$\textcircled{2} i_{out} = \frac{V_{id}}{2} \left[\frac{g_{m4}}{g_{m3}} g_{m1} + g_{m2} \right] - V_s \left[\frac{g_{m4}}{g_{m3}} g_{m1} - g_{m2} \right]$$

Plug $\textcircled{1}$ into $\textcircled{2}$,

$$i_{out} = \frac{V_{id}}{2} \left[\frac{g_{m4}}{g_{m3}} g_{m1} + g_{m2} \right] - \frac{(g_{m1} - g_{m2}) r_{tail} \frac{V_{id}}{2}}{1 + (g_{m1} + g_{m2}) r_{tail}} \left[\frac{g_{m4}}{g_{m3}} g_{m1} - g_{m2} \right]$$

$$\Rightarrow i_{out} = \frac{V_{id}}{2} \left\{ \frac{g_{m4}}{g_{m3}} g_{m1} \left[1 - \frac{(g_{m1} - g_{m2}) r_{tail}}{1 + (g_{m1} + g_{m2}) r_{tail}} \right] + g_{m2} \left[1 + \frac{(g_{m1} - g_{m2}) r_{tail}}{1 + (g_{m1} + g_{m2}) r_{tail}} \right] \right\}$$

$$G_m [d_m] = \frac{i_{out}}{V_{id}}$$

$$= \frac{1}{2} \left\{ \frac{g_{m4}}{g_{m3}} g_{m1} \left[1 - \frac{(g_{m1} - g_{m2}) r_{tail}}{1 + (g_{m1} + g_{m2}) r_{tail}} \right] + g_{m2} \left[1 + \frac{(g_{m1} - g_{m2}) r_{tail}}{1 + (g_{m1} + g_{m2}) r_{tail}} \right] \right\}$$

$$\frac{(g_{m1} - g_{m2}) r_{tail}}{1 + (g_{m1} + g_{m2}) r_{tail}} \approx \frac{(g_{m1} - g_{m2})}{g_{m1} + g_{m2}}$$

$$= \frac{\Delta g_{m1,2}}{2 g_{m1,2}}$$

$$\text{where, } g_{m1} = g_{m1,2} + \frac{\Delta g_{m1,2}}{2}$$

$$g_{m2} = g_{m1,2} - \frac{\Delta g_{m1,2}}{2}$$

$$\text{Also, } g_{m3} = g_{m3,4} + \frac{\Delta g_{m3,4}}{2}$$

$$g_{m4} = g_{m3,4} - \frac{\Delta g_{m3,4}}{2}$$

$$G_m [d_m] =$$

$$\frac{1}{2} \left\{ \frac{1 - \frac{\Delta g_{m3,4}}{2 g_{m3,4}}}{1 + \frac{\Delta g_{m3,4}}{2 g_{m3,4}}} g_{m1,2} \left(\frac{1 + \frac{\Delta g_{m1,2}}{2 g_{m1,2}}}{2 g_{m1,2}} \right) \left(\frac{1 - \frac{\Delta g_{m1,2}}{2 g_{m1,2}}}{2 g_{m1,2}} \right) + g_{m1,2} \left(1 - \frac{\Delta g_{m1,2}}{2 g_{m1,2}} \right) \left(1 + \frac{\Delta g_{m1,2}}{2 g_{m1,2}} \right) \right\}$$

4-34

$$G_m[d_m] = \frac{1}{2} g_{m_{1,2}} \left(1 - \frac{\Delta g_{m_{1,2}}}{2g_{m_{1,2}}} \right) \left(1 + \frac{\Delta g_{m_{1,2}}}{2g_{m_{1,2}}} \right) \cdot \left[\frac{1 - \frac{\Delta g_{m_{3,4}}}{2g_{m_{3,4}}}}{1 + \frac{\Delta g_{m_{3,4}}}{2g_{m_{3,4}}}} + 1 \right]$$

$$\approx \frac{1}{2} g_{m_{1,2}} \left[1 - \left(\frac{\Delta g_{m_{1,2}}}{2g_{m_{1,2}}} \right)^2 \right] \left(\frac{2}{1 + \frac{\Delta g_{m_{3,4}}}{2g_{m_{3,4}}}} \right)$$

$$\approx g_{m_{1,2}} \left[\frac{1 - \left(\frac{\Delta g_{m_{1,2}}}{2g_{m_{1,2}}} \right)^2}{1 + \frac{\Delta g_{m_{3,4}}}{2g_{m_{3,4}}}} \right]$$

(Exact if $r_{tail} \rightarrow \infty$)

Numerical values :

$$g_{m_{1,2}} = \frac{1.05 + 0.95}{2} = 1 \text{ mA/V}$$

$$\Delta g_{m_{1,2}} = 1.05 - 0.95 = 0.1 \text{ mA/V}$$

$$g_{m_{3,4}} = \frac{1.1 + 0.9}{2} = 1 \text{ mA/V}$$

$$\Delta g_{m_{3,4}} = 1.1 - 0.9 = 0.2 \text{ mA/V}$$

$$G_m[d_m] = \frac{1}{1.1} \left[1 - (0.05)^2 \right]$$

$$\approx 0.9068 \text{ mA/V}$$

without mismatch

$$G_m[d_m] = g_{m_{1,2}} = 1 \text{ mA/V}$$

DIFFERENTIAL PAIR WITH ACTIVE LOAD WITH MISMATCH

* FIND GM[DM]

```
GM1 3 5 1 5 1.05M
RO1 3 5 0.95MEG
GM2 4 5 0 5 0.95M
RO2 4 5 1.05MEG
GM3 3 0 3 0 1.1M
RO3 3 0 1MEG
GM4 4 0 3 0 0.9M
RO4 4 0 1MEG
RTAIL 5 0 0.5MEG
```

* SHORT THE OUTPUT TO FIND THE TRANSCONDUCTANCE

```
VOUT 4 0 0
VI 1 0 0 AC 1
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF I(VOUT) VI
.END
```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```
I(VOUT)/VI = 9.060E-04
INPUT RESISTANCE AT VI = 1.000E+20
OUTPUT RESISTANCE AT I(VOUT) = 5.240E+05
```

4.19

$$(a) \quad i_2 = g_{m2}(V_{ic} - V_1) - \frac{V_1}{r_{o2}}$$

$$V_1 = (i_1 + i_2) r_{tail}$$

$$i_2 = g_{m2} [V_{ic} - (i_1 + i_2) r_{tail}] - \frac{(i_1 + i_2) r_{tail}}{r_{o2}}$$

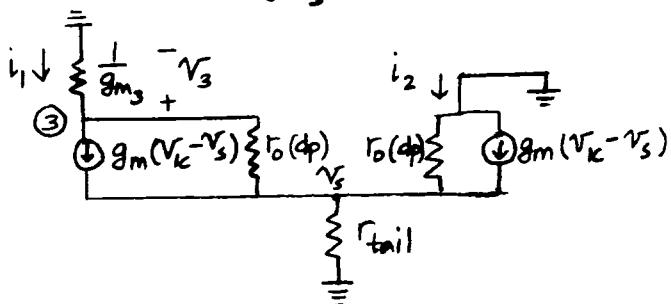
$$i_1 = i_2 (1 - Ed)$$

$$i_2 = g_{m2} [V_{ic} - (i_2 - i_2 Ed + i_2) r_{tail}] - \frac{(i_2 - i_2 Ed + i_1) r_{tail}}{r_{o2}}$$

$$i_2 \left[1 + g_{m2} r_{tail} (2 - Ed) + (2 - Ed) \frac{r_{tail}}{r_{o2}} \right] = g_{m2} V_{ic}$$

$$\begin{aligned} \frac{i_2}{V_{ic}} &= \frac{g_{m2}}{1 + g_{m2} r_{tail} (2 - Ed) + (2 - Ed) \frac{r_{tail}}{r_{o2}}} \\ &\approx \frac{g_{m2}}{1 + g_{m2} r_{tail} (2 - Ed) + 2 \frac{r_{tail}}{r_{o2}}} \\ &\approx \frac{g_{m2}}{2 g_{m2} r_{tail}} = \frac{1}{2 r_{tail}} \end{aligned}$$

(b) First suppose mismatch = 0. Find Ed from $\frac{1}{g_{m3}} \neq 0$ alone.



$$i_1 = g_m (V_{ic} - V_1) + \frac{V_3 - V_1}{r_{o(dp)}}$$

$$i_1 = g_m (V_{ic} - V_1) - \frac{V_1}{r_{o(dp)}} - \frac{i_1}{g_{m3} r_{o(dp)}}$$

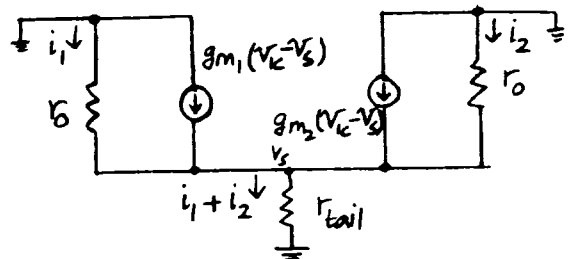
$$i_1 \left(1 + \frac{1}{g_{m3} r_{o(dp)}} \right) = g_m (V_{ic} - V_1) - \frac{V_1}{r_{o}} = i_2$$

$$\frac{i_1}{i_2} = \frac{1}{1 + \frac{1}{g_{m3} r_{o(dp)}}}$$

$$Ed = 1 - \frac{i_1}{i_2} = \frac{1 + \frac{1}{g_{m3} r_{o(dp)}} - 1}{1 + \frac{1}{g_{m3} r_{o(dp)}}} \approx \frac{1}{g_{m3} r_{o(dp)}}$$

This result is consistent with (4.173)

(c) Next, assume $\frac{1}{g_{m3}} = 0$ and $r_{o1} = r_{o2}$. Find Ed from $g_{m1} \neq g_{m2}$ alone.



$$i_1 = g_{m1} (V_{ic} - V_1) - \frac{V_1}{r_{o}} \rightarrow (1)$$

$$\begin{aligned} i_2 &= g_{m2} (V_{ic} - V_1) - \frac{V_1}{r_{o}} \\ &= g_{m2} \left(i_1 + \frac{V_1}{r_{o}} \right) \frac{1}{g_{m1}} - \frac{V_1}{r_{o}} \quad (\text{from (1)}) \\ &= \frac{g_{m2}}{g_{m1}} i_1 + \frac{V_1}{r_{o}} \left(\frac{g_{m2}}{g_{m1}} - 1 \right) \end{aligned}$$

$$V_S = (i_1 + i_2) r_{tail}$$

$$i_2 = \frac{g_{m2}}{g_{m1}} i_1 + \frac{(i_1 + i_2) r_{tail}}{r_o} \left(\frac{g_{m2}}{g_{m1}} - 1 \right)$$

$$i_2 = i_1 \left[\frac{g_{m2}}{g_{m1}} + \frac{r_{tail}}{r_o} \left(\frac{g_{m2}}{g_{m1}} - 1 \right) \right] + i_2 \frac{r_{tail}}{r_o} \left(\frac{g_{m2}}{g_{m1}} - 1 \right)$$

$$i_2 \left[1 + \frac{r_{tail}}{r_o} \left(1 - \frac{g_{m2}}{g_{m1}} \right) \right] = i_1 \left[\frac{g_{m2}}{g_{m1}} + \frac{r_{tail}}{r_o} \left(\frac{g_{m2}}{g_{m1}} - 1 \right) \right]$$

$$\frac{i_1}{i_2} = \frac{1 + \frac{r_{tail}}{r_o} \left(1 - \frac{g_{m2}}{g_{m1}} \right)}{\frac{g_{m2}}{g_{m1}} + \frac{r_{tail}}{r_o} \left(\frac{g_{m2}}{g_{m1}} - 1 \right)}$$

$$= \frac{1 + \frac{r_{tail}}{r_o} \left(1 - \frac{g_{m2}}{g_{m1}} \right)}{\frac{g_{m2}}{g_{m1}} \left(1 + \frac{r_{tail}}{r_o} \right) - \frac{r_{tail}}{r_o}}$$

$$\epsilon_d = 1 - \frac{i_1}{i_2}$$

$$= \frac{\frac{g_{m2}}{g_{m1}} + \frac{r_{tail}}{r_o} \left(\frac{g_{m2}}{g_{m1}} - 1 \right) - 1 - \frac{r_{tail}}{r_o} \left(1 - \frac{g_{m2}}{g_{m1}} \right)}{\frac{g_{m2}}{g_{m1}} \left(1 + \frac{r_{tail}}{r_o} \right) - \frac{r_{tail}}{r_o}}$$

$$\approx \frac{\frac{g_{m2}}{g_{m1}} - 1 + 2 \frac{r_{tail}}{r_o} \left(\frac{g_{m2}}{g_{m1}} - 1 \right)}{\frac{g_{m2}}{g_{m1}}}$$

$$\approx \left(\frac{g_{m2}}{g_{m1}} - 1 \right) \left(1 + \frac{2 r_{tail}}{r_o} \right)$$

$$\frac{g_{m2}}{g_{m1}}$$

$$\approx \left(1 - \frac{g_{m1}}{g_{m2}} \right) \left[1 + \frac{2 r_{tail}}{r_o} \right]$$

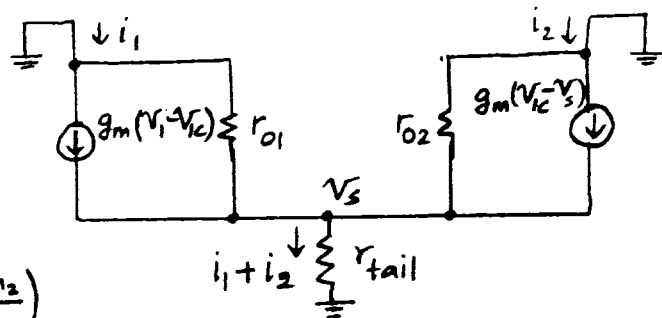
$$= \frac{g_{m2} - g_{m1}}{g_{m2}} \left[1 + \frac{2 r_{tail}}{r_o} \right]$$

$$\approx \frac{-\Delta g_m}{g_m - \frac{\Delta g_m}{2}} \left[1 + \frac{2 r_{tail}}{r_o} \right]$$

$$\approx \frac{-\Delta g_m}{g_m} \left(1 + \frac{\Delta g_m}{2 g_m} \right) \left[1 + \frac{2 r_{tail}}{r_o} \right]$$

$$\approx \frac{-\Delta g_m}{g_m} \left[1 + \frac{2 r_{tail}}{r_o} \right]$$

(d) Next assume $\frac{1}{g_{m3}} = 0$. Find ϵ_d from $r_{o1} \neq r_{o2}$ alone.



$$i_1 = g_m (V_{IC} - V_S) - \frac{V_S}{r_{o1}}$$

$$i_2 = g_m (V_{IC} - V_S) - \frac{V_S}{r_{o2}}$$

$$= g_m (V_{IC} - V_S) - \frac{V_S}{r_{o1}} + \frac{V_S}{r_{o1}} - \frac{V_S}{r_{o2}}$$

$$\underbrace{\phantom{g_m (V_{IC} - V_S) - \frac{V_S}{r_{o1}} + \frac{V_S}{r_{o1}}}}_{i_1}$$

$$i_2 = i_1 + (i_1 + i_2) r_{tail} \left(\frac{1}{r_{o1}} - \frac{1}{r_{o2}} \right)$$

$$i_2 \left[1 - r_{tail} \left(\frac{1}{r_{o1}} - \frac{1}{r_{o2}} \right) \right]$$

$$= i_1 \left[1 + r_{tail} \left(\frac{1}{r_{o1}} - \frac{1}{r_{o2}} \right) \right]$$

$$\frac{i_1}{i_2} = \frac{1 - r_{tail} \left(\frac{1}{r_{o1}} - \frac{1}{r_{o2}} \right)}{1 + r_{tail} \left(\frac{1}{r_{o1}} - \frac{1}{r_{o2}} \right)}$$

$$E_d = 1 - \frac{i_1}{i_2} = \frac{1 + r_{tail} \left(\frac{1}{r_{o1}} - \frac{1}{r_{o2}} \right) - 1 + r_{tail} \left(\frac{1}{r_{o1}} - \frac{1}{r_{o2}} \right)}{1 + r_{tail} \left(\frac{1}{r_{o1}} - \frac{1}{r_{o2}} \right)}$$

$$= \frac{2 r_{tail} \left(\frac{1}{r_{o1}} - \frac{1}{r_{o2}} \right)}{1 + r_{tail} \left(\frac{1}{r_{o1}} - \frac{1}{r_{o2}} \right)} \approx 2 r_{tail} \left(\frac{1}{r_{o1}} - \frac{1}{r_{o2}} \right)$$

$$r_{o1} = r_o(dp) + \Delta r_o(dp)/2$$

$$r_{o2} = r_o(dp) - \Delta r_o(dp)/2$$

$$\frac{1}{r_{o1}} - \frac{1}{r_{o2}} = \frac{1}{r_o(dp) + \frac{\Delta r_o(dp)}{2}} - \frac{1}{r_o(dp) - \frac{\Delta r_o(dp)}{2}}$$

$$= \frac{-\Delta r_o(dp)}{r_o^2(dp) - \frac{\Delta r_o^2(dp)}{4}}$$

ignore

$$\approx \frac{-\Delta r_o(dp)}{r_o^2(dp)}$$

$$E_d \approx -2 \frac{r_{tail}}{r_o(dp)} \frac{\Delta r_o(dp)}{r_o(dp)}$$

(e) Total $E_d \approx \frac{1}{g_{m3} r_o(dp)} - \frac{2 r_{tail} \Delta r_o(dp)}{r_o(dp) r_o(dp)}$

$$- \frac{\Delta g_m(dp)}{g_m(dp)} \left[1 + \frac{2 r_{tail}}{r_o(dp)} \right]$$

(same as 4.186)

(f) $E_m = \frac{1}{1 + g_{m3} r_{o3}} + \frac{(g_{m3} - g_{m4}) r_{o3}}{1 + g_{m3} r_{o3}}$

$$\approx \frac{1}{g_{m3} r_{o3}} + \frac{g_{m3} - g_{m4}}{g_{m3}}$$

$$\approx \frac{1}{g_{m3} r_{o3}} + \frac{\Delta g_{m3,4}}{g_{m3,4} + \frac{\Delta g_{m3,4}}{2}}$$

$$\approx \frac{1}{g_{m3} r_{o3}} + \frac{\Delta g_{m3,4}}{g_{m3,4} \left(1 + \frac{\Delta g_{m3,4}}{2 g_{m3,4}} \right)}$$

$$\approx \frac{1}{g_{m3} r_{o3}} + \frac{\Delta g_{m3,4}}{g_{m3,4}} \left(1 - \frac{\Delta g_{m3,4}}{2 g_{m3,4}} \right)$$

$$\approx \frac{1}{g_{m3} r_{o3}} + \frac{\Delta g_{m3,4}}{g_{m3,4}}$$

(same as 4.187)

(g) $G_m[CM] \approx - \frac{E_d + E_m}{2 r_{tail}}$

Numerical values:

$$E_d = \frac{1}{1.1m(1000)} - \frac{0.1}{1} \left[1 + 2 \frac{0.5}{1} \right]$$

$$\approx -0.0991$$

$$E_m \approx \frac{1}{1.1m(1000)} + \frac{0.2}{1} = 0.2009$$

$$G_m[CM] \approx \frac{-0.0991 + 0.2009}{2(0.5M)}$$

$$= -1.02 \times 10^{-7} A/V$$

$$CMRR = \frac{G_m[dm]}{G_m[CM]} \approx 8880$$

DIFFERENTIAL PAIR WITH ACTIVE LOAD WITH MISMATCH
* FIND GM[CM]

```
GM1 3 5 1 5 1.05M
RO1 3 5 0.95MEG
GM2 4 5 1 5 0.95M
RO2 4 5 1.05MEG
GM3 3 0 3 0 1.1M
RO3 3 0 1MEG
GM4 4 0 3 0 0.9M
RO4 4 0 1MEG
RTAIL 5 0 0.5MEG
```

* SHORT THE OUTPUT TO FIND THE TRANSCONDUCTANCE

```
VOUT 4 0 0
VI 1 0 0 AC 1
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.TF I(VOUT) VI
.END
```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```
I(VOUT)/VI = -9.237E-08
INPUT RESISTANCE AT VI = 1.000E+20
OUTPUT RESISTANCE AT I(VOUT) = 5.240E+05
```

From SPICE,

$$CMRR = \left| \frac{0.906 \times 10^{-3}}{-9.237 \times 10^{-8}} \right| = 9810$$

Without mismatch

From (4.186),

$$\begin{aligned} \epsilon_d &\approx \frac{1}{g_{m3} r_{o(dp)}} \\ &= \frac{1}{1m(1Meg)} = \frac{1}{1000} \end{aligned}$$

From (4.187),

$$\begin{aligned} \epsilon_m &\approx \frac{1}{g_{m3} r_{o3}} \\ &= \frac{1}{1m(1Meg)} = \frac{1}{1000} \end{aligned}$$

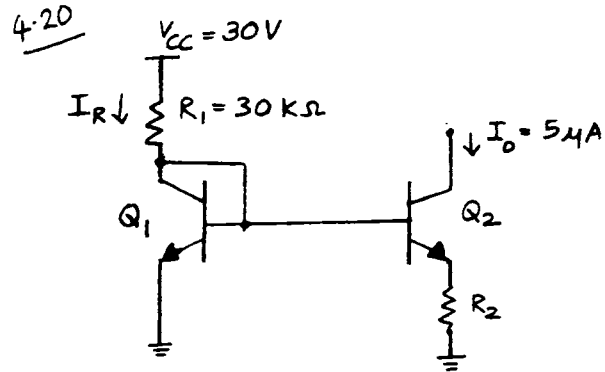
From (4.185),

$$\begin{aligned} G_m[cm] &\approx -\frac{\epsilon_d + \epsilon_m}{2r_{tail}} \\ &\approx -\frac{2}{1000} = -2 \times 10^{-9} A/V \\ &\approx -\frac{2}{2(0.5Meg)} \end{aligned}$$

CMRR (without mismatch)

$$= \frac{1 mA/V}{2 \times 10^{-9} A/V} = 500,000$$

So, mismatch reduces CMRR



$$I_R = \frac{V_{CC} - V_{BE(on)}}{R_1} = \frac{30 - 0.7}{30k} = 0.977mA$$

$$V_{BE1} = V_{BE2} + I_O R_2$$

$$\therefore I_O R_2 = V_T \ln \frac{I_{C1}}{I_O} \approx V_T \ln \frac{I_R}{I_O}$$

$$\therefore R_2 = \frac{V_T}{I_O} \ln \frac{I_R}{I_O} = \frac{26mV}{54A} \ln \frac{0.977mA}{54A}$$

$$= 27.4k\Omega$$

$$R_O = r_{o2} \left(1 + \frac{g_{m2} R_2}{1 + \frac{g_{m2} R_2}{\beta_o}} \right)$$

$$r_{o2} = \frac{130V}{54A} = 26M\Omega$$

$$R_2 = 27.4k\Omega$$

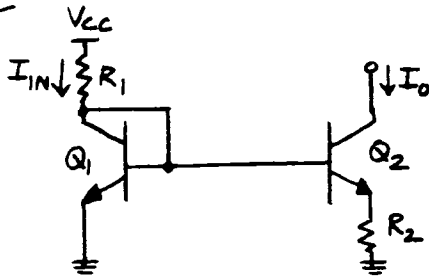
$$g_{m2} = \frac{1}{26} \frac{5}{1000} = 1.9 \times 10^{-4} A/V$$

$$\beta_o = 200$$

$$R_O = 26 \left(1 + \frac{1.9 \times 10^{-4} \times 27.4 \times 10^3}{1 + \frac{1.9 \times 10^{-4} \times 27.4 \times 10^3}{200}} \right)$$

$$= 158M\Omega$$

4.21



$$I_{IN} = \frac{V_{CC} - V_{BE(on)}}{R_1} = \frac{V'}{R_1}$$

where $V' = V_{CC} - V_{BE(on)}$

$$I_O R_2 = V_T \ln \frac{I_{IN}}{I_O}$$

$$\therefore I_O R_2 = V_T \ln \frac{V'}{I_O R_1}$$

$$\therefore R_2 = \frac{V_T}{I_O} \ln \frac{V'}{I_O R_1}$$

$$\text{Let } f = R_1 + R_2 = R_1 + \frac{V_T}{I_O} \ln \frac{V'}{I_O R_1}$$

$$\frac{df}{dR_1} = 1 + \frac{V_T}{I_O} \frac{I_O R_1}{V'} \left(\frac{-V'}{I_O R_1^2} \right)$$

$$= 1 - \frac{V_T}{I_O} \frac{1}{R_1} = 0$$

$$\therefore R_1 = \frac{V_T}{I_O} \text{ and}$$

$$R_2 = \frac{V_T}{I_O} \ln \left(\frac{V'}{I_O} \frac{I_O}{V_T} \right)$$

These give minimum total resistance for given V_{CC} and I_O

For Problem (4.20), $V_{CC} = 30V$ and

$$I_O = 5 \mu A.$$

$$\therefore R_1 = \frac{26 \text{ mV}}{5 \mu A} = 5.2 \text{ k}\Omega$$

$$R_2 = \frac{26 \text{ mV}}{5 \mu A} \ln \frac{29.3}{0.026} = 36.5 \text{ k}\Omega$$

This value of R_1 is too small in

practice as the current drawn from the supply is about

$$\frac{30 - 0.7}{5.2 \text{ k}} \approx 5.6 \text{ mA which is quite}$$

high

4.22

Circuit as shown in fig (4.31a)

with $V_{CC} = 15V$, $R_1 = 20 \text{ k}\Omega$, $R_2 = 10 \text{ k}\Omega$

$$I_{IN} = \frac{15 - 0.7}{20 \text{ k}\Omega} = 0.72 \text{ mA}$$

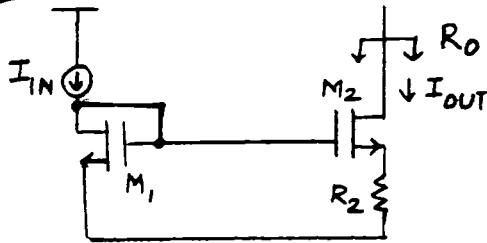
$$I_{OUT} R_2 = V_T \ln \frac{I_{IN}}{I_{OUT}} \approx V_T \ln \frac{I_{IN}}{I_{OUT}}$$

$$I_{OUT} = \frac{V_T}{R_2} \ln \frac{I_{IN}}{I_{OUT}} = 2.6 \times 10^{-6} \ln \frac{0.72 \text{ mA}}{I_{OUT}}$$

By trial and error we find out,

$$I_{OUT} \approx 10.9 \mu A$$

4.23

Ignore BE. $X_d = L_d = 0$

$$V_{OV1} = \sqrt{\frac{2I_{IN}}{K'(W/L)_1}}$$

$$\left(\frac{W}{L}\right)_1 = \frac{2I_{IN}}{K'(V_{OV1})^2} = \frac{200}{194(0.2)^2} = 25.8$$

$$\sqrt{I_{OUT}} = \frac{-\sqrt{\frac{2}{K'(W/L)_2}} + \sqrt{\frac{2}{K'(W/L)_2} + 4R_2V_{OV1}}}{2R_2} \times \frac{\sqrt{2K'(W/L)_2}}{\sqrt{2K'(W/L)_2}}$$

$$g_{m2}R_2 = -1 + \sqrt{1 + 2R_2V_{OV1}K'(W/L)_2} \rightarrow \textcircled{1}$$

$$R_O = r_{o2}(1 + g_{m2}R_2)$$

$$g_{m2}R_2 = \frac{R_O}{r_{o2}} - 1$$

$$V_A = \frac{L}{dX_d/dV_{DS}} = \frac{1}{0.02} = 50$$

$$r_{o2} = \frac{50}{10\mu} = 5\text{ M}\Omega$$

$$R_O = 50\text{ M}\Omega$$

$$g_{m2}R_2 = 10 - 1 = 9 \rightarrow \textcircled{2}$$

Putting $\textcircled{2}$ in $\textcircled{1}$,

$$1 + 2R_2V_{OV1}K'(W/L)_2 = 100$$

$$2R_2V_{OV1}K'(W/L)_2 = 99 \rightarrow \textcircled{3}$$

$$\text{swing} = I_{OUT}R_2 + V_{OV2}$$

$$R_2 = \frac{\text{swing} - V_{OV2}}{I_{OUT}}$$

$$I_{OUT}R_2 = \text{swing} - \sqrt{\frac{2I_{OUT}}{K'(W/L)_2}}$$

where from $\textcircled{3}$, we can put

$$(W/L)_2 = 99 / (2R_2V_{OV1}K')$$

$$I_{OUT}R_2 = \text{swing} - \sqrt{\frac{2I_{OUT}}{K'} \frac{2R_2V_{OV1}K'}{99}}$$

$$I_{OUT}R_2 + \sqrt{\frac{4}{99}V_{OV1}I_{OUT}} \sqrt{R_2} - \text{swing} = 0$$

which gives

$$\sqrt{R_2} = \frac{-\sqrt{\frac{4}{99}V_{OV1}I_{OUT}} \pm \sqrt{\frac{4}{99}V_{OV1}I_{OUT} + 4I_{OUT}\text{swing}}}{2I_{OUT}}$$

 $\sqrt{R_2}$ must be greater than zero,

$$\begin{aligned} \therefore \sqrt{R_2} &= \frac{-\sqrt{\frac{4}{99}(0.2)10^{-5}} + \sqrt{\frac{4}{99}(0.2)10^{-5} + 4 \times 10^{-5}(0.2)}}{2 \times 10^{-5}} \\ &= \frac{2.5584 \times 10^{-3}}{2 \times 10^{-5}} = 128 \end{aligned}$$

$$R_2 = 16.36\text{ k}\Omega$$

$$\left(\frac{W}{L}\right)_2 = \frac{99}{2(16.36\text{ k})(0.2)(196 \frac{\mu\text{A}}{\text{V}})} = 77.2$$

4.24

(a) $I_{OUT} = 0.1 \mu A$ when $I_{IN} = 1 \mu A$

$$I_{OUT} = I_{IN} \exp \left[-\frac{I_{IN} R}{n V_T} \right] \quad (4.206)$$

$$\Rightarrow R = \frac{n V_T}{I_{IN}} \ln \frac{I_{IN}}{I_{OUT}}$$

$$R = \frac{(1.5)(26 \text{ mV})}{(1 \mu A)} \ln 10 = 90 \text{ k}\Omega$$

To keep transistor in weak inversion

 $V_{GS} - V_t < 0$. Input transistor conducts more current,

$$I_{IN} = \frac{W}{L} I_t \exp \left[\frac{V_{GS1} - V_t}{n V_T} \right]$$

$$n V_T \ln \frac{I_{IN}}{\frac{W}{L} I_t} = V_{GS1} - V_t < 0$$

$$\therefore I_{IN} < \frac{W}{L} I_t$$

$$\frac{W}{L} > \frac{I_{IN}}{I_t} = \frac{1 \mu A}{0.1 \mu A} = 10$$

(b) $I_{OUT} = 0.1 \mu A$ when $R = 10 \text{ k}\Omega$

$$\ln \frac{I_{IN}}{I_{OUT}} = \frac{I_{IN} R}{n V_T}$$

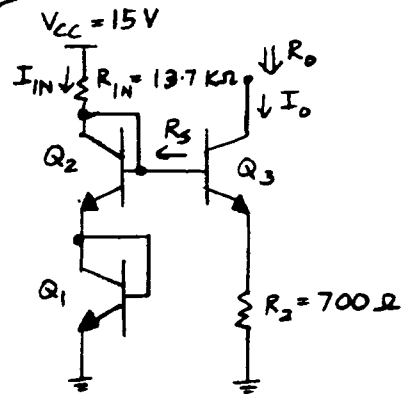
Trial & Error :

I_{IN}	$\ln \frac{I_{IN}}{I_{OUT}}$	$\frac{I_{IN} R}{n V_T}$
1 μA	2.3	0.256
10 μA	4.6	2.56
20 μA	5.29	5.12
21 μA	5.35	5.38

So, $I_{IN} \approx 21 \mu A$

$$\frac{W}{L} > \frac{I_{IN}}{I_t} = \frac{21 \mu A}{0.1 \mu A} = 210$$

4.25



Assume :

$$I_S = 5 \times 10^{-15} \text{ A}$$

$$\beta_o = 200$$

$$V_{BE1} + V_{BE2} = V_{BE3} + I_O R_2$$

$$I_{C1} \approx I_{C2} = I_{IN} ; I_O = I_{E3}$$

$$I_{IN} = \frac{15 - 2 \times 0.7}{13.7 \text{ k}} = 0.993 \text{ mA}$$

$$V_T \ln \frac{I_{C1}}{I_S} + V_T \ln \frac{I_{C2}}{I_S} = V_T \ln \frac{I_O}{I_S} + I_O R_2$$

$$\therefore I_O = \frac{V_T}{R_2} \ln \frac{I_{IN}^2}{I_O I_S} = \frac{26 \text{ mV}}{700 \Omega} \ln \frac{(0.993 \times 10^{-3})^2}{(5 \times 10^{-15} I_O)}$$

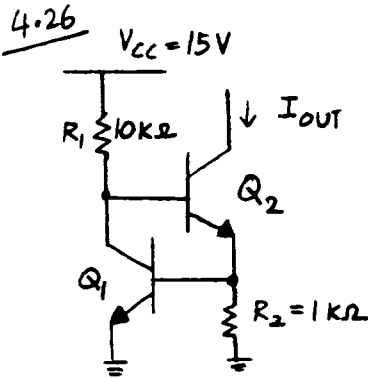
By trial and error, $I_O = 0.97 \text{ mA}$ R_S is the equivalent resistancelooking into the base of Q_2

$$R_S \approx \frac{2}{g_m} = 2 \frac{V_T}{I_{IN}} = 52 \Omega \ll r_{\pi 3}$$

Where $r_{\pi 3} \approx 2.6 \text{ k}\Omega$ $\therefore g_{m3} = \frac{1}{26}$

$$R_O = r_{o3} \left(1 + \frac{g_{m3} R_2}{1 + g_{m3} R_2} \right) = 3.2 \text{ M}\Omega$$

$$\text{Where, } r_{o3} = \frac{V_A}{I_O} \approx 130 \text{ k}\Omega$$



$$S = \frac{V_{CC}}{I_{OUT}} \frac{\partial I_{OUT}}{\partial V_{CC}}$$

For this circuit

$$I_{OUT} \approx \frac{V_{BE1}}{R_2}$$

$$I_{C1} = \frac{V_{CC} - V_{BE1} - V_{BE2}}{R_1} \text{ and}$$

$$V_{BE1} = V_T \ln \frac{I_{C1}}{I_S}$$

$$\therefore I_{OUT} = \frac{V_T}{R_2} \ln \frac{V_{CC} - V_{BE1} - V_{BE2}}{I_S R_1}$$

If $V_{BE(on)} \ll V_{CC}$ then,

$$\frac{\partial I_{OUT}}{\partial V_{CC}} \approx \frac{V_T}{R_2} \frac{1}{V_{CC} - V_{BE1} - V_{BE2}}$$

$$\text{and } S = \frac{V_{CC}}{I_{OUT}} \frac{V_T}{R_2} \frac{1}{V_{CC} - V_{BE1} - V_{BE2}}$$

$$I_{C1} \approx \frac{15 - 0.7 - 0.7}{10} = 1.36 \text{ mA}$$

$$\therefore V_{BE1} = 26 \ln \frac{1.36 \times 10^{-3}}{5 \times 10^{-5}} \text{ mV}$$

$$= 0.685 \text{ V}$$

$$\therefore I_{OUT} = \frac{0.685}{1} = 0.685 \text{ mA}$$

$$\therefore S = \frac{15}{0.685 \times 10^{-3}} \frac{26 \times 10^{-3}}{1000} \frac{1}{13.6} = 0.04$$

4.27

From (4.245),
 $V_{BE(on)} = V_T \ln I_1 T^{-\gamma} E e^{V_{G0}/V_T}$

$$\text{Put } I_1 = I_0 [1 - K_1 (T - T_0)]$$

$$\text{where } K_1 = 1500 \times 10^{-6}$$

$$\therefore V_{BE(on)} = V_T \left[\ln \{ I_0 [1 - K_1 (T - T_0)] \} \right. \\ \left. - \gamma \ln T + \ln E + \frac{V_{G0}}{V_T} \right]$$

$$= V_{G0} - V_T \left[\gamma \ln T - \ln E - \ln I_0 \right. \\ \left. - \ln \{ 1 - K_1 (T - T_0) \} \right]$$

$$\approx V_{G0} - V_T [\gamma \ln T - \ln E I_0] - V_T K_1 (T - T_0)$$

Using $\ln(1+x) \approx x$,

$$\text{Now, } V_{OUT} = V_{BE(on)} + K V_T$$

$$\therefore V_{OUT} = V_{G0} - V_T \gamma \ln T + V_T (K + \ln E I_0) \\ - V_T K_1 (T - T_0) \rightarrow \textcircled{1}$$

$$\frac{dV_{OUT}}{dT} \Big|_{T=T_0} = 0, \text{ then}$$

$$\frac{V_{T_0}}{T_0} (K + \ln E I_0) - \frac{V_{T_0}}{T_0} \gamma \ln T_0 - \frac{V_{T_0}}{T_0} \gamma \\ - V_{T_0} K_1 = 0$$

$$\therefore K + \ln E I_0 = \gamma \ln T_0 + \gamma + K_1 T_0 \rightarrow \textcircled{2}$$

$\textcircled{2} \rightarrow \textcircled{1}$ gives,

$$V_{OUT} = V_{G0} + V_T \gamma \ln \frac{T_0}{T} + V_T \gamma - V_T K_1 (T - 2T_0)$$

$$\text{At } T = T_0, V_{OUT} = V_{G0} + V_{T_0} \gamma + V_{T_0} K_1 T_0$$

$$\text{If } T_0 = 298^\circ \text{K}, K_1 = 1500 \times 10^{-6}$$

$$V_{T_0} = 26 \text{ mV}, V_{G0} = 1.205 \text{ V}$$

$$\therefore V_{OUT} = 1.205 + 3.2 \times 26 \times 10^{-3} \\ + 26 \times 10^{-3} \times 1500 \times 10^{-6} \times 298 \\ = 1.2996 \text{ V}$$

4.28

For zero TC_F of V_{OUT} at $25^\circ C$

We require $V_{OUT} = 1.262 V$

$$V_{OUT} = V_{BE1} + \frac{R_2}{R_3} (V_{BE1} - V_{BE2})$$

$$= V_{BE1} + 0.1 \frac{R_2}{R_3}$$

If $I_1 = 200 \mu A$, then

$$V_{BE1} = V_T \ln \frac{200 \times 10^{-6}}{5 \times 10^{-15}} = 0.635 V$$

$$\therefore 1.262 = 0.635 + 0.1 \frac{R_2}{R_3}$$

$$\therefore \frac{R_2}{R_3} = 6.27 \rightarrow \textcircled{1}$$

$$\text{Also, } R_1 = \frac{V_{OUT} - V_{BE1}}{I_1} = \frac{1.262 - 0.635}{200 \times 10^{-6}}$$

$$= 3.135 k\Omega$$

$$\text{Now, } V_{BE2} = V_{BE1} - 0.1 = 0.535 V$$

$$\therefore I_2 = I_s e^{V_{BE2}/V_T} = 5 \times 10^{-15} e^{535/26}$$

$$= 4.32 \mu A$$

$$\therefore R_2 + R_3 = \frac{1.262 - 0.535}{4.32 \times 10^{-6}} = 168.3 k\Omega$$

$$\text{From } \textcircled{1}, R_2 = 6.23 R_3$$

$$\therefore 6.23 R_3 + R_3 = 168.3 k\Omega$$

$$\therefore R_3 = 23.1 k\Omega, R_2 = 145.2 k\Omega$$

4.29

$$V_{EB2} = V_T \ln \frac{I_{C2}}{I_{S2}} = V_T \ln \frac{I_{E2}}{I_{S2}}$$

(because base current is ignored)

$$I_{E2} = \frac{\Delta V_{EB}}{R_3}$$

Now double I_s , and I_{S2} . ΔV_{EB} is

constant. See (4.272). Therefore,

I_{E2} and I_{C2} are constant. So,

V_{EB2} changes by $V_T \ln \frac{1}{2} = -18 mV$

From (4.248),

$$V_{EB2} = V_{G0} - V_T [(\gamma - \alpha) \ln T - \ln(EG)]$$

$$\frac{dV_{EB2}}{dT} = \frac{-V_T(\gamma - \alpha)}{T} - (\gamma - \alpha) \ln T \frac{V_T}{T} + \frac{V_T \ln(EG)}{T}$$

$$= \frac{-V_T(\gamma - \alpha) - V_T[(\gamma - \alpha) \ln T - \ln(EG)] + V_{G0} - V_{G0}}{T}$$

$$= \frac{V_{EB2} - V_{G0} - V_T(\gamma - \alpha)}{T}$$

Under nominal conditions, the slope of the V_{EB2} term and the slope of the ΔV_{EB} term at the output are set equal in magnitude and opposite in polarity at $25^\circ C$ to set $TC_F = 0$.

However, under the specified

conditions, V_{EB2} has fallen by 18 mV, and its slope has fallen by $\frac{18 mV}{25 + 273}$

$$= \frac{18}{298} = 60 \mu V/K = 60 \mu V/^\circ C$$

since V_{EB2} contributes directly to the output (see 4.266), the output slope changes by the same amount.

$$\text{Therefore, } \left. \frac{dV_{OUT}}{dT} \right|_{T=25^\circ C} = -60 \mu V/^\circ C$$

4.30

With I_{s1} and I_{s2} adjusted from the nominal value but the gain equal to the nominal value, SPICE gives

$$\left. \frac{dV_{OUT}}{dT} \right|_{T=25^{\circ}\text{C}} = -60 \mu\text{V}/^{\circ}\text{C}$$

With the gain readjusted so that $V_{OUT} = \text{target}$ at 25°C ,

$$\left. \frac{dV_{OUT}}{dT} \right|_{T=25^{\circ}\text{C}} = 0$$

Therefore, the case of $I_s \neq \text{nominal}$ can be corrected by trimming the gain to set the output equal to the target.

4-45

BAND-GAP REFERENCE (CASE 1)

* CASE 1: Q1 AND Q2 NORMAL;
* R3 ADJUSTED FOR TC=0 AT 25 DEG C

* IN CASE 1, D(VOUT)/DT = 0 AT T = 25 DEGREES C:
* VOUT (AT T = 0 DEGREES C) = 1.1606 VOLTS
* VOUT (AT T = 25 DEGREES C) = 1.1608 VOLTS
* VOUT (AT T = 50 DEGREES C) = 1.1606 VOLTS

Q1 0 0 1 MOD1
Q2 0 0 2 MOD2
R1 4 1 1K
R2 4 3 8K
R3 3 2 2.39K
E1 4 0 1 3 10K

.MODEL MOD1 PNP IS=1.25E-17
.MODEL MOD2 PNP IS=1E-16

.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.TEMP 0 25 50
.END

**** OPERATING POINT INFORMATION TNOM= 27 TEMP= 0
NODE=VOLTAGE NODE=VOLTAGE NODE=VOLTAGE
+0:1 = 8.3348E-01 0:2 = 7.3560E-01 0:3 = 8.3336E-01
+0:4 = 1.1606E+00

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT
ELEMENT 0:Q1 0:Q2
MODEL 0:MOD1 0:MOD2
IB -3.2389E-06 -4.0501E-07
IC -3.2389E-04 -4.0501E-05
VBE -8.3348E-01 -7.3560E-01
VCE -8.3348E-01 -7.3560E-01
VBC 0. 0.
VS 0. 0.
POWER 2.7266E-04 3.0090E-05
BETAD 1.0000E+02 1.0000E+02
GM 1.3761E-02 1.7207E-03
RPI 7.2670E+03 5.8115E+04
RX 0. 0.
RO 1.7378E+17 2.1722E+16
BETAAC 9.9999E+01 9.9999E+01

**** OPERATING POINT INFORMATION TNOM= 27 TEMP= 25
NODE=VOLTAGE NODE=VOLTAGE NODE=VOLTAGE
+0:1 = 8.0368E-01 0:2 = 6.9683E-01 0:3 = 8.0356E-01
+0:4 = 1.1608E+00

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT
ELEMENT 0:Q1 0:Q2
MODEL 0:MOD1 0:MOD2
IB -3.5359E-06 -4.4213E-07
IC -3.5359E-04 -4.4213E-05
VBE -8.0368E-01 -6.9683E-01
VCE -8.0368E-01 -6.9683E-01
VBC 0. 0.
VS 0. 0.
POWER 2.8701E-04 3.1117E-05
BETAD 1.0000E+02 1.0000E+02
GM 1.3763E-02 1.7209E-03
RPI 7.2660E+03 5.8109E+04
RX 0. 0.
RO 2.7965E+15 3.4956E+14
BETAAC 9.9999E+01 9.9999E+01

**** OPERATING POINT INFORMATION TNOM= 27 TEMP= 50
NODE=VOLTAGE NODE=VOLTAGE NODE=VOLTAGE
+0:1 = 7.7351E-01 0:2 = 6.5771E-01 0:3 = 7.7339E-01
+0:4 = 1.1606E+00

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT
ELEMENT 0:Q1 0:Q2
MODEL 0:MOD1 0:MOD2
IB -3.8328E-06 -4.7924E-07
IC -3.8328E-04 -4.7924E-05
VBE -7.7351E-01 -6.5771E-01
VCE -7.7351E-01 -6.5771E-01
VBC 0. 0.
VS 0. 0.
POWER 2.9943E-04 3.1835E-05
BETAD 9.9999E+01 1.0000E+02
GM 1.3764E-02 1.7210E-03
RPI 7.2652E+03 5.8104E+04
RX 0. 0.
RO 8.4155E+13 1.0519E+13
BETAAC 9.9999E+01 9.9999E+01

4-46

BAND-GAP REFERENCE (CASE 2)

* CASE 2: ISAT IN Q1 AND Q2 DOUBLED;
* R3 SAME AS IN CASE 1
*

* IN CASE 2,

* $D(V_{OUT})/DT = (1.1443 \text{ VOLTS} - 1.1413 \text{ VOLTS})/(50 \text{ DEGREES C})$
* $= -60 \text{ MICROVOLTS/(DEGREE C) AT } T = 25 \text{ DEG C:}$

* $V_{OUT} \text{ (AT } T = 0 \text{ DEGREES C)} = 1.1443 \text{ VOLTS}$
* $V_{OUT} \text{ (AT } T = 25 \text{ DEGREES C)} = 1.1430 \text{ VOLTS}$
* $V_{OUT} \text{ (AT } T = 50 \text{ DEGREES C)} = 1.1413 \text{ VOLTS}$

Q1 0 0 1 MOD1
Q2 0 0 2 MOD2
R1 4 1 1K
R2 4 3 8K
R3 3 2 2.39K
E1 4 0 1 3 10K

* THE SATURATION CURRENTS HERE ARE DOUBLED FROM CASE 1

.MODEL MOD1 PNP IS=2.5E-17

.MODEL MOD2 PNP IS=2E-16

.OPTIONS NOMOD NOPAGE

.WIDTH OUT=80

.OP

.TEMP 0 25 50

.END

**** OPERATING POINT INFORMATION TNOM= 27 TEMP= 0
NODE=VOLTAGE NODE=VOLTAGE NODE=VOLTAGE
+0:1 = 8.1717E-01 0:2 = 7.1928E-01 0:3 = 8.1705E-01
+0:4 = 1.1443E+00

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT
ELEMENT 0:Q1 0:Q2
MODEL 0:MOD1 0:MOD2
IB -3.2390E-06 -4.0502E-07
IC -3.2390E-04 -4.0502E-05
VBE -8.1717E-01 -7.1928E-01
VCE -8.1717E-01 -7.1928E-01
VBC 0. 0.
VS 0. 0.
POWER 2.6733E-04 2.9424E-05
BETAD 1.0000E+02 1.0000E+02
GM 1.3761E-02 1.7207E-03
RPI 7.2669E+03 5.8114E+04
RX 0. 0.
RO 8.6891E+16 1.0861E+16
BETAAC 9.9999E+01 9.9999E+01

**** OPERATING POINT INFORMATION TNOM= 27 TEMP= 25
NODE=VOLTAGE NODE=VOLTAGE NODE=VOLTAGE
+0:1 = 7.8587E-01 0:2 = 6.7903E-01 0:3 = 7.8575E-01
+0:4 = 1.1430E+00

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT
ELEMENT 0:Q1 0:Q2
MODEL 0:MOD1 0:MOD2
IB -3.5359E-06 -4.4213E-07
IC -3.5359E-04 -4.4213E-05
VBE -7.8587E-01 -6.7903E-01
VCE -7.8587E-01 -6.7903E-01
VBC 0. 0.
VS 0. 0.
POWER 2.8066E-04 3.0322E-05
BETAD 1.0000E+02 1.0000E+02
GM 1.3763E-02 1.7209E-03
RPI 7.2659E+03 5.8108E+04
RX 0. 0.
RO 1.3982E+15 1.7478E+14
BETAAC 9.9999E+01 9.9999E+01

**** OPERATING POINT INFORMATION TNOM= 27 TEMP= 50
NODE=VOLTAGE NODE=VOLTAGE NODE=VOLTAGE
+0:1 = 7.5421E-01 0:2 = 6.3841E-01 0:3 = 7.5409E-01
+0:4 = 1.1413E+00

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT
ELEMENT 0:Q1 0:Q2
MODEL 0:MOD1 0:MOD2
IB -3.8329E-06 -4.7925E-07
IC -3.8329E-04 -4.7925E-05
VBE -7.5421E-01 -6.3841E-01
VCE -7.5421E-01 -6.3841E-01
VBC 0. 0.
VS 0. 0.
POWER 2.9197E-04 3.0902E-05
BETAD 1.0000E+02 1.0000E+02
GM 1.3764E-02 1.7211E-03
RPI 7.2650E+03 5.8103E+04
RX 0. 0.
RO 4.2077E+13 5.2597E+12
BETAAC 9.9999E+01 9.9999E+01

4-47

BAND-GAP REFERENCE (CASE 3)
 * CASE 3: ISAT IN Q1 AND Q2 DOUBLED;
 * R3 ADJUSTED TO MAKE VOUT = TARGET IN CASE 1
 *

* IN CASE 3,
 * R3 IS ADJUSTED UNTIL VOUT (AT T = 25 DEGREES C)
 * IS EQUAL TO 1.1608 V (THE TARGET FROM CASE 1)
 * UNDER THIS CONDITION,
 * THE RESULTING D(VOUT)/DT = 0 AT T = 25 DEGREES C:
 * VOUT (AT T = 0 DEGREES C) = 1.1606 VOLTS
 * VOUT (AT T = 25 DEGREES C) = 1.1608 VOLTS
 * VOUT (AT T = 50 DEGREES C) = 1.1606 VOLTS

Q1 0 0 1 MOD1
 Q2 0 0 2 MOD2
 R1 4 1 1K
 R2 4 3 8K
 * R3 IS ADJUSTED TO MAKE VOUT = TARGET IN CASE 1
 R3 3 2 2.2835K
 E1 4 0 1 3 10K

* THE SATURATION CURRENTS HERE ARE DOUBLED FROM CASE 1
 .MODEL MOD1 PNP IS=2.5E-17
 .MODEL MOD2 PNP IS=2E-16

.OPTIONS NOMOD NOPAGE
 .WIDTH OUT=80
 .OP
 .TEMP 0 25 50
 .END

**** OPERATING POINT INFORMATION TNOM= 27 TEMP= 0
 NODE=VOLTAGE NODE=VOLTAGE NODE=VOLTAGE
 +0:1 = 8.1824E-01 0:2 = 7.2036E-01 0:3 = 8.1812E-01
 +0:4 = 1.1606E+00

**** BIPOLAR JUNCTION TRANSISTORS
 SUBCKT
 ELEMENT 0:Q1 0:Q2
 MODEL 0:MOD1 0:MOD2
 IB -3.3901E-06 -4.2390E-07
 IC -3.3901E-04 -4.2390E-05
 VBE -8.1824E-01 -7.2036E-01
 VCE -8.1824E-01 -7.2036E-01
 VBC 0. 0.
 VS 0. 0.
 POWER 2.8016E-04 3.0841E-05
 BETAD 1.0000E+02 1.0000E+02
 GM 1.4403E-02 1.8010E-03
 RPI 6.9431E+03 5.5526E+04
 RX 0. 0.
 RO 8.6891E+16 1.0861E+16
 BETAAC 9.9999E+01 9.9999E+01

**** OPERATING POINT INFORMATION TNOM= 27 TEMP= 25
 NODE=VOLTAGE NODE=VOLTAGE NODE=VOLTAGE
 +0:1 = 7.8704E-01 0:2 = 6.8020E-01 0:3 = 7.8692E-01
 +0:4 = 1.1608E+00

**** BIPOLAR JUNCTION TRANSISTORS
 SUBCKT
 ELEMENT 0:Q1 0:Q2
 MODEL 0:MOD1 0:MOD2
 IB -3.7008E-06 -4.6275E-07
 IC -3.7008E-04 -4.6275E-05
 VBE -7.8704E-01 -6.8020E-01
 VCE -7.8704E-01 -6.8020E-01
 VBC 0. 0.
 VS 0. 0.
 POWER 2.9418E-04 3.1791E-05
 BETAD 1.0000E+02 1.0000E+02
 GM 1.4405E-02 1.8011E-03
 RPI 6.9421E+03 5.5520E+04
 RX 0. 0.
 RO 1.3982E+15 1.7478E+14
 BETAAC 9.9999E+01 9.9999E+01

**** OPERATING POINT INFORMATION TNOM= 27 TEMP= 50
 NODE=VOLTAGE NODE=VOLTAGE NODE=VOLTAGE
 +0:1 = 7.5548E-01 0:2 = 6.3968E-01 0:3 = 7.5536E-01
 +0:4 = 1.1606E+00

**** BIPOLAR JUNCTION TRANSISTORS
 SUBCKT
 ELEMENT 0:Q1 0:Q2
 MODEL 0:MOD1 0:MOD2
 IB -4.0116E-06 -5.0160E-07
 IC -4.0116E-04 -5.0160E-05
 VBE -7.5548E-01 -6.3968E-01
 VCE -7.5548E-01 -6.3968E-01
 VBC 0. 0.
 VS 0. 0.
 POWER 3.0610E-04 3.2407E-05
 BETAD 1.0000E+02 1.0000E+02
 GM 1.4406E-02 1.8013E-03
 RPI 6.9413E+03 5.5515E+04
 RX 0. 0.
 RO 4.2077E+13 5.2597E+12
 BETAAC 9.9999E+01 9.9999E+01

4.31 With $V_{OS} = 0$

From (4.266),

$$V_{OUT} = V_{EB_2} + V_{R_3} + V_{R_2}$$

From (4.264),

$$V_{R_3} = V_{EB_1} - V_{EB_2}$$

Therefore,

$$V_{OUT} = V_{EB_2} + V_{EB_1} - V_{EB_2} + V_{R_2}$$

$$V_{OUT} = V_{EB_1} + V_{R_2}$$

From (4.265),

$$V_{OUT} = V_{EB_1} + \frac{R_2}{R_3} \Delta V_{EB}$$

Since $\Delta V_{EB} \propto V_T$,

$$V_{OUT} = V_{EB_1} + K V_T \text{ where } K \propto \frac{R_2}{R_3}$$

Therefore, if R_3 is 1% low, then

K is 1% high.

Thus,

$$V_{OUT} = V_{OUT}|_{nom} + 0.01 K V_T$$

$$\text{since } \left. \frac{dV_{OUT}|_{nom}}{dT} \right|_{T=T_0} = 0$$

$$\left. \frac{dV_{OUT}}{dT} \right|_{T=T_0} = 0.01 K \frac{V_{T_0}}{T_0}$$

$$\begin{aligned} \text{Now, } K V_{T_0} &= V_{OUT}|_{T=T_0} - V_{EB_1}|_{T=T_0} \\ &\approx 1.26 - 0.6 \approx 0.66 \text{ V} \end{aligned}$$

$$\begin{aligned} \therefore \left. \frac{dV_{OUT}}{dT} \right|_{T=T_0} &= 0.01 \frac{0.66}{298^\circ \text{K}} \\ &= 22 \text{ } \mu\text{V}/^\circ\text{C} \end{aligned}$$

4.32

$$(a) I_{C_2} = \frac{V_{BE_1} - V_{BE_2}}{R_3}$$

Negative feedback forces

$$V_{C_2} = V_{BE_1} - V_{OS}$$

$$V_{OUT} = V_{BE_1} - V_{OS} + (V_{BE_1} - V_{BE_2}) \frac{R_2}{R_3}$$

Therefore, the output-referred offset is equal to $-V_{OS}$ here

From (4.271),

$$\left. \frac{dV_{OUT}}{dT} \right|_{T=T_0} = - \frac{V_{OS}(OUT)}{T_0}$$

$$\left. \frac{dV_{OUT}}{dT} \right|_{T=298^\circ K} = \frac{30 \text{ mV}}{298} = 101 \text{ } \mu\text{V}/^\circ\text{C}$$

$$\sqrt{\frac{W}{L}} = \sqrt{\frac{2I}{K'(T=298^\circ K)}} \left(\frac{n}{2m \cdot 298} \right) \left(\frac{T}{298} \right)^{\frac{n}{2}-1}$$

$$\frac{W}{L} = \frac{2I}{K'(T=298^\circ K)} \left[\frac{n}{2m(298)} \right]^2 \left(\frac{T}{298} \right)^{2(\frac{n}{2}-1)}$$

Make $\frac{dV_{GS}}{dT} = 0$ at $T=298^\circ K$

$$\begin{aligned} \frac{W}{L} &= \frac{2I}{K'(T=298^\circ K)} \left[\frac{n}{2m(298)} \right]^2 \\ &= \frac{2(200)}{194} \left[\frac{1.5}{2(0.002)(298)} \right]^2 \\ &= 3.265 \end{aligned}$$

(b) $V_{OS} > 0$ reduces V_{OUT} so pick R_2 too big. This magnifies the ΔV_{BE} term, $\therefore \frac{dV_{OUT}}{dT} > 0$

4.33

$$V_{GS} = V_t + V_{OV}$$

$$V_{GS} = V_t(T=298^\circ K) - M \Delta T + \sqrt{\frac{2I}{K'(T=298^\circ K) \left(\frac{I}{298} \right)^n \frac{W}{L}}}$$

$$V_{GS} = V_t(T=298^\circ K) - M \Delta T + V_{OV}(T=298^\circ K) \left(\frac{I}{298} \right)^{\frac{n}{2}}$$

$$\frac{dV_{GS}}{dT} = -M + V_{OV}(T=298^\circ K) \frac{n}{2} \left(\frac{I}{298} \right)^{\frac{n}{2}-1} \frac{1}{298} = 0$$

$$\sqrt{\frac{2I}{K'(T=298^\circ K) \frac{W}{L}}} \frac{n}{2} \left(\frac{I}{298} \right)^{\frac{n}{2}-1} \frac{1}{298} = m$$

4.34

Since $M_3 = M_4$, $|I_{D3}| = |I_{D4}| = I_{D1} =$

$$I_{D2} = I_{BIAS}$$

$$I_{BIAS} R = V_{GS1} - V_{GS2}$$

$$I_{BIAS} = \frac{1}{R} \left(V_{t1} - \sqrt{\frac{I_{BIAS}}{\frac{\mu_n C_{ox}}{2} \left(\frac{W}{L}\right)_1}} - V_{t2} - \sqrt{\frac{I_{BIAS}}{\frac{\mu_n C_{ox}}{2} \left(\frac{W}{L}\right)_2}} \right)$$

Ignoring body effect,

$$V_{t1} = V_{t2}$$

$$I_{BIAS} = \frac{1}{R} \sqrt{\frac{2 I_{BIAS}}{\mu_n C_{ox}}} \left(\sqrt{\left(\frac{L}{W}\right)_1} - \sqrt{\left(\frac{L}{W}\right)_2} \right)$$

$$\therefore I_{BIAS} = \frac{2}{R^2 \mu_n C_{ox}} \left(\sqrt{\left(\frac{L}{W}\right)_1} - \sqrt{\left(\frac{L}{W}\right)_2} \right)^2$$

$$\frac{1}{I_{BIAS}} \frac{dI_{BIAS}}{dT} = -\frac{1}{\mu_n} \frac{d\mu_n}{dT} - \frac{2}{R} \frac{dR}{dT}$$

$$(4.243), \mu_n \propto T^{-n}$$

$$\therefore -\frac{1}{\mu_n} \frac{d\mu_n}{dT} > 0$$

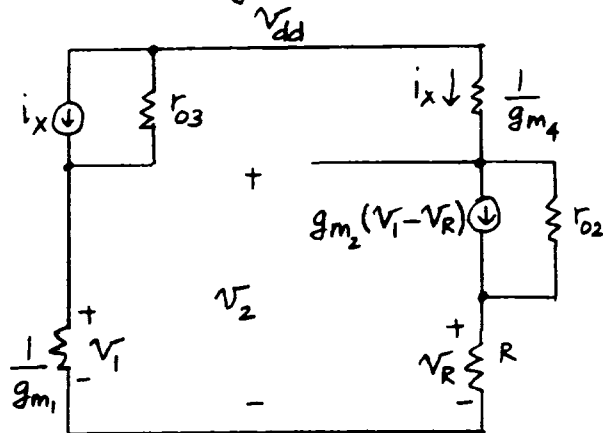
$$(2.11), R \propto \mu_2^{-1} \propto T^n$$

$$\therefore \frac{2}{R} \frac{dR}{dT} > 0$$

Here μ_x is the mobility of the specific doping material used for the resistor. The above two terms tend to cancel each other.

4.35

small-signal model



$$KCL: i_x = \frac{V_1 - V_{dd}}{r_{03}} + V_1 g_{m1}$$

$$\rightarrow V_1 \left(\frac{1}{r_{03}} + g_{m1} \right) = i_x + \frac{V_{dd}}{r_{03}}$$

$$V_2 = V_{dd} - \frac{i_x}{g_{m4}} = V_R + V_{r_{02}}$$

$$= i_x R + [i_x - g_{m2}(V_1 - V_R)] r_{02}$$

SO,

$$V_{dd} - \frac{i_x}{g_{m4}} = i_x R + i_x r_{02} - g_{m2} r_{02} V_1 + g_{m2} r_{02} i_x R$$

$$V_{dd} = i_x \left(R + r_{02} + g_{m2} r_{02} R + \frac{1}{g_{m4}} \right) - \frac{g_{m2} r_{02} (i_x + V_{dd}/r_{03})}{g_{m1} + 1/r_{03}}$$

$$V_{dd} \left(1 + \frac{g_{m2} r_{02}}{1 + g_{m1} r_{03}} \right) = i_x \left(R + r_{02} + \frac{g_{m2} r_{02} R + \frac{1}{g_{m4}} - \frac{g_{m2} r_{02} \cdot r_{03}}{1 + g_{m1} r_{03}}}{g_{m1} + 1/r_{03}} \right)$$

$$\text{Assume } r_{02} \approx r_{03}, \quad \approx -\frac{g_{m2} r_{02}}{g_{m1}}$$

$$\frac{I_{bias}}{V_{dd}} = \frac{i_x}{V_{dd}} \approx \frac{1 + g_{m2}/g_{m1}}{g_{m2} r_{02} \left(R - \frac{1}{g_{m1}} \right)}$$

$$\approx \frac{1 + g_{m2}/g_{m1}}{g_{m2} r_{02} R}$$

4.36

$$\left(\frac{W}{L}\right)_1 = \frac{100 \mu\text{m}}{1 \mu\text{m}} \left(\frac{W}{L}\right)_2 = \frac{50 \mu\text{m}}{1 \mu\text{m}}$$

Ignore channel length modulation
for top mosfet current mirror.

Then $|I_{D3}| = |I_{D4}|$ and $I_{D1} = I_{D2}$
Also ignore base currents $|I_{C1}| = |I_{C2}|$

$$V_{GS1} + V_T \ln \frac{|I_{C1}|}{I_{S1}} = V_{GS2} + V_T \ln \frac{|I_{C2}|}{I_{S2}}$$

$$V_{GS2} - V_{GS1} = V_T \ln \frac{I_{C1}}{I_{C2}} \frac{I_{S2}}{I_{S1}} = V_T \ln 10$$

Neglect body effect, $V_{t1} \approx V_{t2}$

$$\therefore \sqrt{\frac{2I_{C1,2}}{\mu_n C_{ox}}} \left(\sqrt{\left(\frac{L}{W}\right)_2} - \sqrt{\left(\frac{L}{W}\right)_1} \right) = V_T \ln 10$$

$$I_{C1,2} = \left(\frac{V_T \ln 10}{\sqrt{\left(\frac{L}{W}\right)_2} - \sqrt{\left(\frac{L}{W}\right)_1}} \right)^2 \frac{\mu_n C_{ox}}{2} = 203 \mu\text{A}$$

$$V_T^2 \propto T^2, \mu_n \propto T^{-n}$$

$$\therefore I_{C1,2} \propto T^{2-n}$$

BIAS CIRCUIT

* IDEAL CASE: LAMBDA=0 AND IGNORE BODY EFFECT
 * ALSO USE INFINITE BETA AND EARLY VOLTAGE
 * AND RB = 0 IN THE BIPOLAR TRANSISTORS

```
VCC 100 0 3 AC 1
M1 3 3 2 2 CMOSN W=100U L=1U
M2 5 3 1 1 CMOSN W=50U L=1U
M3 3 4 100 100 CMOSP W=50U L=1U
M4 4 4 100 100 CMOSP W=50U L=1U
Q1 0 0 1 PNP 10
Q2 0 0 2 PNP
```

* THE FOLLOWING ELEMENT IS INSERTED TO MEASURE IBIAS
 VIBIAS 4 5 0

```
.MODEL PNP PNP IS=2E-15 BF=1E8 VAF=1E8
.MODEL CMOSN NMOS LEVEL=1 VTO=0.6 KP=194U
.MODEL CMOSP PMOS LEVEL=1 VTO=-0.8 KP=65U
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.TF I(VIBIAS) VCC
.END
```

```
**** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000
      NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:1      = 5.956E-01 0:2      = 6.552E-01 0:3      = 1.398E+00
+0:4      = 1.848E+00 0:5      = 1.848E+00 0:100     = 3.000E+00
```

SUBCKT

```
ELEMENT 0:Q1      0:Q2
MODEL    0:PNP      0:PNP
IB       -2.005E-12 -2.005E-12
IC       -2.005E-04 -2.005E-04
VBE      -5.956E-01 -6.552E-01
VCE      -5.956E-01 -6.552E-01
VBC      0.          0.
VS       0.          0.
POWER    1.194E-04 1.314E-04
BETAD    1.000E+08 1.000E+08
GM       7.753E-03 7.753E-03
RPI      1.289E+10 1.289E+10
RX       0.          0.
RO       3.599E+11 4.801E+11
BETAAC   9.999E+07 9.999E+07
```

**** MOSFETS

SUBCKT

```
ELEMENT 0:M1      0:M2      0:M3      0:M4
MODEL    0:CMOSN  0:CMOSN  0:CMOSP  0:CMOSP
ID       2.005E-04 2.005E-04 -2.005E-04 -2.005E-04
IBS      0.        0.        0.        0.
IBD      -7.438E-15 -1.253E-14 1.601E-14 1.151E-14
VGS      7.438E-01 8.033E-01 -1.151E+00 -1.151E+00
VDS      7.438E-01 1.253E+00 -1.601E+00 -1.151E+00
VBS      0.        0.        0.        0.
VTH      6.000E-01 6.000E-01 -8.000E-01 -8.000E-01
VDSAT    1.438E-01 2.033E-01 -3.513E-01 -3.513E-01
BETA     1.940E-02 9.700E-03 3.250E-03 3.250E-03
GAM EFF  0.        0.        0.        0.
GM       2.789E-03 1.972E-03 1.142E-03 1.142E-03
GDS      0.        0.        0.        0.
GMB      0.        0.        0.        0.
```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```
I(VIBIAS)/VCC      = 1.346E-11
INPUT RESISTANCE AT VCC      = 3.456E+10
OUTPUT RESISTANCE AT I(VIBIAS) = 1.457E+11
```

BIAS CIRCUIT

* REAL CASE: LAMBDA > 0 AND INCLUDE BODY EFFECT
 * ALSO USE FINITE BETA AND EARLY VOLTAGE
 * AND RB > 0 IN THE BIPOLAR TRANSISTORS

```
VCC 100 0 3 AC 1
M1 3 3 2 0 CMOSN W=100U L=1U
M2 5 3 1 0 CMOSN W=50U L=1U
M3 3 4 100 100 CMOSP W=50U L=1U
M4 4 4 100 100 CMOSP W=50U L=1U
Q1 0 0 1 PNP 10
Q2 0 0 2 PNP
```

* THE FOLLOWING ELEMENT IS INSERTED TO MEASURE IBIAS
 VIBIAS 4 5 0

```
.MODEL PNP PNP IS=2E-15 BF=50 VAF=50 RB=300
.MODEL CMOSN NMOS LEVEL=1 VTO=0.6 KP=194U
+ LD=0.09U TOX=80E-10 LAMBDA=0.02439 GAMMA=0.283
.MODEL CMOSP PMOS LEVEL=1 VTO=-0.8 KP=65U
+ LD=0.09U TOX=80E-10 LAMBDA=0.04878
* COX = 3.9(8.854E-14)/(80E-8) = 4.32E-7
* GAMMA = SQRT(2(Q)(EPSILON)(NA))/COX
* GAMMAN =
* SQRT(2(1.6E-19)(11.7)(8.854E-14)(4E16+5E15))/4.32E-7 = 0.283
* GAMMAP DOESN'T MATTER
```

* BECAUSE THERE IS NO BODY EFFECT ON M3 AND M4
 * LAMBDA_{DM} = (D_{SD}/D_{VS})/LEFF = 0.02/0.82 = 0.02439 V⁻¹(-1)
 * LAMBDA_{PM} = (D_{SD}/D_{VS})/LEFF = 0.04/0.82 = 0.04878 V⁻¹(-1)
 * CHANNEL-LENGTH MODULATION HAS A SIGNIFICANT EFFECT.
 * IN PRACTICE, CASCODES ARE USUALLY USED TO REDUCE THIS EFFECT
 * WHEREVER * THE POWER-SUPPLY VOLTAGE IS LARGE ENOUGH
 * TO ACCOMMODATE THE CASCODES. FOR EXAMPLE, SEE FIG. 4.50,
 * WHERE CASCODES ARE APPLIED TO A VBE REFERENCE.

```
.OPTIONS NOMOD NOPAGE
.WIDTH OUT=80
.OP
.TF I(VIBIAS) VCC
.END
```

```
**** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000
      NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:1      = 6.104E-01 0:2      = 6.722E-01 0:3      = 1.545E+00
+0:4      = 1.786E+00 0:5      = 1.786E+00 0:100     = 3.000E+00
```

SUBCKT

```
ELEMENT 0:Q1      0:Q2
MODEL    0:PNP      0:PNP
IB       -7.046E-06 -7.124E-06
IC       -3.523E-04 -3.562E-04
VBE      -6.104E-01 -6.722E-01
VCE      -6.104E-01 -6.722E-01
VBC      0.          0.
VS       -2.114E-04 -2.137E-03
POWER    2.194E-04 2.442E-04
BETAD    5.000E+01 5.000E+01
GM       1.361E-02 1.377E-02
RPI      3.670E+03 3.630E+03
RX       3.000E+01 3.000E+02
RO       1.419E+05 1.403E+05
BETAAC   4.997E+01 4.997E+01
```

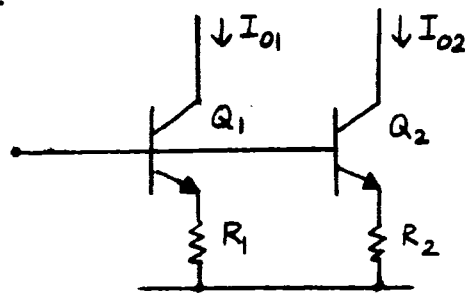
**** MOSFETS

SUBCKT

```
ELEMENT 0:M1      0:M2      0:M3      0:M4
MODEL    0:CMOSN  0:CMOSN  0:CMOSP  0:CMOSP
ID       3.633E-04 3.594E-04 -3.633E-04 -3.594E-04
IBS      -6.722E-15 -6.104E-15 0.        0.
IBD      -1.546E-14 -1.786E-14 1.454E-14 1.214E-14
VGS      8.734E-01 9.352E-01 -1.213E+00 -1.213E+00
VDS      8.734E-01 1.175E+00 -1.454E+00 -1.213E+00
VBS      -6.722E-01 -6.104E-01 0.        0.
VTH      7.000E-01 6.921E-01 -8.000E-01 -8.000E-01
VDSAT    1.734E-01 2.430E-01 -4.138E-01 -4.138E-01
BETA     2.416E-02 1.217E-02 4.245E-03 4.198E-03
GAM EFF  2.830E-01 2.830E-01 0.        0.
GM       4.190E-03 2.957E-03 1.756E-03 1.737E-03
GDS      8.677E-06 8.520E-06 1.655E-05 1.655E-05
GMB      5.257E-04 3.804E-04 0.        0.
```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```
I(VIBIAS)/VCC      = 8.374E-05
INPUT RESISTANCE AT VCC      = 5.445E+03
OUTPUT RESISTANCE AT I(VIBIAS) = 3.410E+04
```

4.37

$$R = \frac{1}{2} (R_1 + R_2), \quad I_C = \frac{1}{2} (I_{O1} + I_{O2})$$

$$\begin{aligned} \frac{\Delta I_C}{I_C} &= \frac{1}{1 + \frac{g_m R}{\kappa}} \frac{\Delta I_S}{I_S} + \frac{\frac{g_m R}{\kappa}}{1 + \frac{g_m R}{\kappa}} \left[-\frac{\Delta R}{R} + \frac{\Delta \kappa}{\kappa} \right] \\ &\approx \frac{1}{1 + g_m R} \frac{\Delta I_S}{I_S} + \frac{g_m R}{1 + g_m R} \left[-\frac{\Delta R}{R} \right] \end{aligned} \rightarrow \textcircled{1}$$

We want $\frac{\Delta I_C}{I_C} = 0.01$

Now $\frac{\Delta I_S}{I_S} = \frac{\Delta V_{BE}}{V_T} = \frac{2}{26} = 0.077$

$$\frac{\Delta R}{R} = 0.005$$

$\therefore$ Worst case in (1)

$$0.01 = \frac{1}{1 + \chi} (0.077) + \frac{\chi}{1 + \chi} (0.005)$$

where $\chi = g_m R$. Solve for χ .

$$\chi = g_m R = 13.4$$

$$\therefore \frac{q I_C R}{k T} = 13.4$$

$$\therefore I_C R = 13.4 \times 26 \text{ mV} = 0.348 \text{ V}$$

4.38

From (4.315),

$$V_{OS} = V_T \left[\frac{\Delta I_{SP}}{I_{SP}} - \frac{\Delta I_{SN}}{I_{SN}} + \frac{2}{\beta_F} \right]$$

Worst case is,

$$V_{OS} = 26 \left(0.05 + 0.05 + \frac{2}{15} \right) \text{ mV} \\ = 6.1 \text{ mV}$$

4.39

If Q_3 and Q_4 have emitter resistors R_3 and R_4 , then

$$\frac{I_{C3}}{\alpha_3} R_3 + V_{BE3} = \frac{I_{C4}}{\alpha_4} R_4 + V_{BE4}$$

From (4.296), the mismatch in

 I_{C3} and I_{C4} is

$$\frac{\Delta I_C}{I_C} \approx \frac{1}{1+g_m R} \frac{\Delta I_S}{I_S} + \frac{g_m R}{1+g_m R} \left[\frac{-\Delta R}{R} + \frac{\Delta \alpha}{\alpha} \right] \\ = \frac{1}{1 + \frac{50 \times 10^{-6}}{26 \times 10^{-3}} (2000)} (0.05) \\ + \frac{3.85}{1+3.85} \left[0.005 + \frac{0.1}{15} \right]$$

$$\left(\text{Using } \frac{\Delta \alpha}{\alpha} = \frac{1}{\beta} \frac{\Delta \beta}{\beta} \right)$$

$$\text{Thus, } \frac{\Delta I_C}{I_C} = 1.96 \times 10^{-2}$$

Again using (4.315) with

$$\frac{\Delta I_{SP}}{I_{SP}} = \frac{\Delta I_C}{I_C} = 1.96 \times 10^{-2}$$

We have

$$V_{OS} = 26 \left[0.0196 + 0.05 + \frac{2}{15} \right] \text{ mV} \\ = 5.3 \text{ mV}$$

4.40 From (4.339),

$$V_{OS} = V_{t1} - V_{t2} + \frac{V_{OVN}}{2} \left[\frac{V_{t3} - V_{t4}}{\frac{|V_{OVp}|}{2}} + \frac{\Delta(W/L)_P}{(W/L)_P} - \frac{\Delta(W/L)_N}{(W/L)_N} \right]$$

$$V_{OVN} = \sqrt{\frac{2(I_{TAIL}/2)}{K'_N (W/L)_N}}$$

$$K'_N = 194 \mu\text{A/V}^2$$

$$(W/L)_N = \frac{(W/L)_1 + (W/L)_2}{2} = 10$$

$$V_{OVN} = \sqrt{\frac{100 \mu}{194 \mu (10)}} = 227 \text{ mV}$$

$$|V_{OVp}| = \sqrt{\frac{2(I_{TAIL}/2)}{K'_P (W/L)_P}}$$

$$K'_P = 65 \mu\text{A/V}^2$$

$$(W/L)_P = \frac{(W/L)_3 + (W/L)_4}{2} = 30$$

$$V_{OVp} = \sqrt{\frac{100 \mu}{65 \mu (30)}} = 227 \text{ mV}$$

Worst case is :

$$V_{OS} = 10 \text{ mV} + \frac{227 \text{ mV}}{2} \left[\frac{20 \text{ mV}}{227 \text{ mV}} + 0.05 + 0.05 \right] \\ = 10 \text{ mV} + 113 \text{ mV} (0.188) = 31.4 \text{ mV}$$

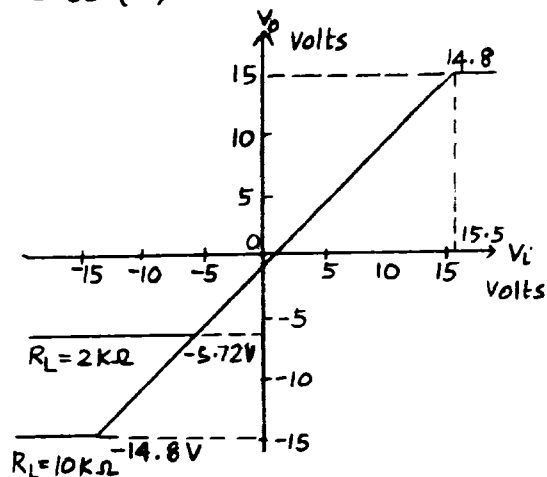
CHAPTER 5

5.1

$$(a) I_R = \frac{V_{CC} - V_{BE3}}{R_3} = \frac{15 - 0.7}{5K} = 2.86 \text{ mA}$$

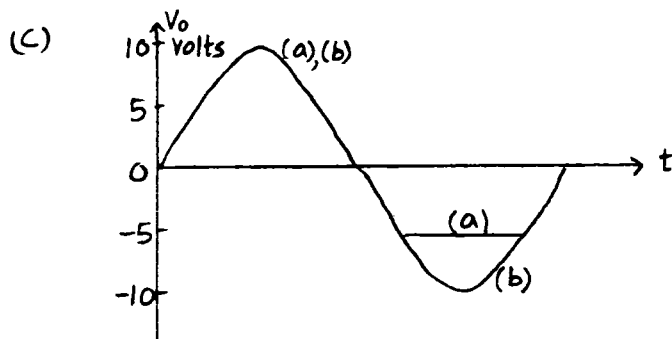
$$\text{Thus, } I_Q = 2.86 \text{ mA}$$

$$I_Q R_L = 2.86 (2) = 5.72 \text{ V}$$



$$(b) I_Q R_L = 2.86 \times 10 = 28.6 \text{ V}$$

Thus, the lower limit on V_o is $(-V_{CC} + V_{CE})$



EMITTER FOLLOWER OUTPUT STAGE, $R_L = 2 \text{ KOHMS}$

```
VCC 100 0 15
VEE 200 0 -15
Q1 100 1 2 NPN
Q2 2 3 200 NPN
Q3 3 3 200 NPN
R3 0 3 5K
RL 2 0 2K
VI 1 0 SIN 0 10 10K 0 0.
.MODEL NPN NPN RB=200 BF=200 VAF=130 IS=5E-15
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.DC VI -16 16 1
.PLOT DC V(2)
.TRAN 4U 200U
.PLOT TRAN V(2)
.FOUR 10K V(2)
.END
```

***** DC TRANSFER CURVES THOM= 27.000 TEMP= 27.000

VOLT	V(2)				
(A)	-1.000E+01	0.	1.000E+01	2.000E+01	3.000E+01
-1.600E+01	-6.02E+00	A*			
-1.500E+01	-6.02E+00	A*			
-1.400E+01	-6.02E+00	A*			
-1.300E+01	-6.02E+00	A*			
-1.200E+01	-6.02E+00	A*			
-1.100E+01	-6.02E+00	A*			
-1.000E+01	-6.02E+00	A*			
-9.000E+00	-6.02E+00	A*			
-8.000E+00	-6.02E+00	A*			
-7.000E+00	-6.02E+00	A*			
-6.000E+00	-6.02E+00	A*			
-5.000E+00	-5.62E+00	A*			
-4.000E+00	-4.66E+00	A*			
-3.000E+00	-3.67E+00	A*			
-2.000E+00	-2.68E+00	A*			
-1.000E+00	-1.69E+00	A*			
0.	-6.99E-01	A*			
1.000E+00	2.96E-01	A*			
2.000E+00	1.29E+00	A*			
3.000E+00	2.28E+00	A*			
4.000E+00	3.28E+00	A*			
5.000E+00	4.28E+00	A*			
6.000E+00	5.27E+00	A*			
7.000E+00	6.27E+00	A*			
8.000E+00	7.27E+00	A*			
9.000E+00	8.26E+00	A*			
1.000E+01	9.26E+00	A*			
1.100E+01	1.02E+01	A*			
1.200E+01	1.12E+01	A*			
1.300E+01	1.22E+01	A*			
1.400E+01	1.32E+01	A*			
1.500E+01	1.42E+01	A*			
1.600E+01	1.49E+01	A*			

**** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:1	= 0.	0:2	== -6.990E-01	0:3	== -1.429E+01
+0:100	= 1.500E+01	0:200	== -1.500E+01		

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT			
ELEMENT	0:Q1	0:Q2	0:Q3
MODEL	0:NPN	0:NPN	0:NPN
IB	1.240E-05	1.416E-05	1.416E-05
IC	2.765E-03	3.127E-03	2.831E-03
VBE	6.990E-01	7.028E-01	7.028E-01
VCE	1.569E+01	1.430E+01	7.028E-01
VBC	-1.500E+01	-1.359E+01	0.
VS	-1.500E+01	6.990E-01	1.429E+01
POWER	4.342E-02	4.473E-02	2.000E-03
BETAD	2.230E+02	2.209E+02	2.000E+02
GM	1.069E-01	1.209E-01	1.094E-01
RPI	2.086E+03	1.827E+03	1.827E+03
RX	2.000E+02	2.000E+02	2.000E+02
RO	5.243E+04	4.591E+04	4.591E+04
BETAAC	2.230E+02	2.208E+02	1.999E+02

***** TRANSIENT ANALYSIS THOM= 27.000 TEMP= 27.000

```

TIME      V(2)
(A)      -1.000E+01 -5.000E+00 0. 5.000E+00 1.000E+01
0. -6.99E-01-----A-----
4.000E-06 1.77E+00 + + + + A + + + +
8.000E-06 4.09E+00 + + + + + A + + +
1.200E-05 6.12E+00 + + + + + + A + +
1.600E-05 7.71E+00 + + + + + + + A +
2.000E-05 8.70E+00 + + + + + + + + A +
2.400E-05 9.20E+00 + + + + + + + + + A +
2.800E-05 9.09E+00 + + + + + + + + + A +
3.200E-05 8.31E+00 + + + + + + + + + A +
3.600E-05 6.97E+00 + + + + + + + + + A +
4.000E-05 5.11E+00-----A-----
4.400E-05 2.93E+00 + + + + + A + + +
4.800E-05 5.39E-01 + + + + + A + + +
5.200E-05 -1.94E+00 + + + + A + + + +
5.600E-05 -4.32E+00 + + + A + + + + +
6.000E-05 -5.74E+00 + + A + + + + + +
6.400E-05 -6.02E+00 + + A + + + + + +
6.800E-05 -6.02E+00 + + A + + + + + +
7.200E-05 -6.02E+00 + + A + + + + + +
7.600E-05 -6.02E+00 + + A + + + + + +
8.000E-05 -6.02E+00-----A-----
8.400E-05 -6.02E+00 + + A + + + + + +
8.800E-05 -6.02E+00 + + A + + + + + +
9.200E-05 -5.45E+00 + + A + + + + + +
9.600E-05 -3.16E+00 + + + A + + + + +
1.000E-04 -6.99E-01 + + + + A + + + +
1.040E-04 1.76E+00 + + + + + A + + +
1.080E-04 4.08E+00 + + + + + + A + +
1.120E-04 6.07E+00 + + + + + + + A +
1.160E-04 7.71E+00 + + + + + + + + A +
1.200E-04 8.70E+00-----A-----
1.240E-04 9.20E+00 + + + + + + + + A +
1.280E-04 9.09E+00 + + + + + + + + + A +
1.320E-04 8.31E+00 + + + + + + + + + A +
1.360E-04 6.97E+00 + + + + + + + + + A +
1.400E-04 5.11E+00 + + + + + + + + + A +
1.440E-04 2.93E+00 + + + + + + A + +
1.480E-04 5.39E-01 + + + + + A + + +
1.520E-04 -1.94E+00 + + + + A + + + +
1.560E-04 -4.32E+00 + + + A + + + + +
1.600E-04 -5.74E+00-----A-----
1.640E-04 -6.02E+00 + + A + + + + + +
1.680E-04 -6.02E+00 + + A + + + + + +
1.720E-04 -6.02E+00 + + A + + + + + +
1.760E-04 -6.02E+00 + + A + + + + + +
1.800E-04 -6.02E+00 + + A + + + + + +
1.840E-04 -6.02E+00 + + A + + + + + +
1.880E-04 -6.02E+00 + + A + + + + + +
1.920E-04 -5.45E+00 + + A + + + + + +
1.960E-04 -3.16E+00 + + + A + + + + +
2.000E-04 -6.99E-01-----A-----

```

***** FOURIER COMPONENTS OF TRANSIENT RESPONSE V(2)

DC COMPONENT = 2.870D-01

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	8.159E+00	1.000E+00	-3.476E-02	0.
2	2.000E+04	1.250E+00	1.533E-01	-8.984E+01	-8.980E+01
3	3.000E+04	6.333E-01	7.761E-02	-2.819E-02	6.576E-03
4	4.000E+04	1.590E-01	1.948E-02	8.787E+01	8.790E+01
5	5.000E+04	8.093E-02	9.919E-03	3.654E+00	3.689E+00
6	6.000E+04	1.156E-01	1.417E-02	8.832E+01	8.835E+01
7	7.000E+04	4.861E-02	5.957E-03	1.722E+02	1.723E+02
8	8.000E+04	2.064E-02	2.530E-03	1.008E+02	1.008E+02
9	9.000E+04	2.816E-02	3.451E-03	1.784E+02	1.784E+02

TOTAL HARMONIC DISTORTION = 1.739E+01 PERCENT

***** EMITTER FOLLOWER OUTPUT STAGE, RL = 10 KOHMS

```

*****
VCC 100 0 15
VEE 200 0 -15
Q1 100 1 2 NPN
Q2 2 3 200 NPN
Q3 3 3 200 NPN
R3 0 3 5K
RL 2 0 10K
VI 1 0 SIN 0 10 10K 0 0
.MODEL NPN NPN RB=200 BF=200 VAF=130 IS=5E-15
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.DC VI -16 16 1
.PLOT DC V(2)
.TRAN 4U 200U
.PLOT TRAN V(2)
.FOUR 10K V(2)
.END

```

***** DC TRANSFER CURVES THOM= 27.000 TEMP= 27.000

```

VOLT      V(2)
(A)      -2.000E+01 -1.000E+01 0. 1.000E+01 2.000E+01
-1.600E+01 -1.49E+01-----A-----
-1.500E+01 -1.49E+01 + A + + + + +
-1.400E+01 -1.46E+01 + A + + + + +
-1.300E+01 -1.36E+01 + + A + + + + +
-1.200E+01 -1.26E+01 + + A + + + + +
-1.100E+01 -1.16E+01 + + A + + + + +
-1.000E+01 -1.06E+01 + + A + + + + +
-9.000E+00 -9.68E+00 + + A + + + + +
-8.000E+00 -8.68E+00 + + + A + + + + +
-7.000E+00 -7.69E+00 + + + A + + + + +
-6.000E+00 -6.69E+00-----A-----
-5.000E+00 -5.69E+00 + + + A + + + + +
-4.000E+00 -4.69E+00 + + + A + + + + +
-3.000E+00 -3.69E+00 + + + + A + + + +
-2.000E+00 -2.69E+00 + + + + A + + + +
-1.000E+00 -1.70E+00 + + + + A + + + +
0. -7.02E-01 + + + + A + + + +
1.000E+00 2.97E-01 + + + + A + + + +
2.000E+00 1.29E+00 + + + + + A + + +
3.000E+00 2.29E+00 + + + + + A + + +
4.000E+00 3.29E+00-----A-----
5.000E+00 4.29E+00 + + + + + A + + +
6.000E+00 5.29E+00 + + + + + A + + +
7.000E+00 6.29E+00 + + + + + + A + +
8.000E+00 7.28E+00 + + + + + + A + +
9.000E+00 8.28E+00 + + + + + + A + +
1.000E+01 9.28E+00 + + + + + + A + +
1.100E+01 1.02E+01 + + + + + + A + +
1.200E+01 1.12E+01 + + + + + + + A +
1.300E+01 1.22E+01 + + + + + + + A +
1.400E+01 1.32E+01-----A-----
1.500E+01 1.42E+01 + + + + + + + A +
1.600E+01 1.49E+01 + + + + + + + A +

```

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:1	= 0.	0:2	= -7.017E-01	0:3	= -1.429E+01
+0:100	= 1.500E+01	0:200	= -1.500E+01		

***** BIPOLAR JUNCTION TRANSISTORS

```

SUBCKT
ELEMENT 0:Q1 0:Q2 0:Q3
MODEL 0:NPN 0:NPN 0:NPN
IB 1.364E-05 1.416E-05 1.416E-05
IC 3.043E-03 3.127E-03 2.831E-03
VBE 7.017E-01 7.028E-01 7.028E-01
VCE 1.570E+01 1.429E+01 7.028E-01
VBC -1.500E+01 -1.359E+01 0.
VS -1.500E+01 7.017E-01 1.429E+01
POWER 4.780E-02 4.472E-02 2.000E-03
BETAD 2.230E+02 2.209E+02 2.000E+02
GM 1.176E-01 1.209E-01 1.094E-01
RPI 1.895E+03 1.827E+03 1.827E+03
RX 2.000E+02 2.000E+02 2.000E+02
RO 4.764E+04 4.591E+04 4.591E+04
BETAAC 2.230E+02 2.208E+02 1.999E+02

```


***** TRANSIENT ANALYSIS THOM= 27.000 TEMP= 27.000

0.	-7.02E-01																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																								
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FOURIER COMPONENTS OF TRANSIENT RESPONSE V(2)

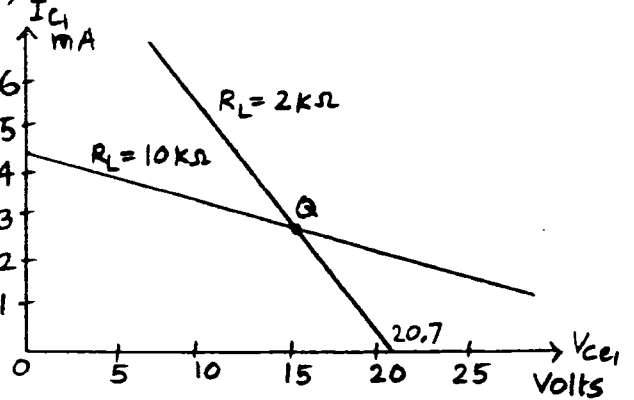
DC COMPONENT = -7.007D-01

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	9.950E+00	1.000E+00	-7.121E-03	0.
2	2.000E+04	1.361E-03	1.368E-04	-4.854E+01	-4.853E+01
3	3.000E+04	5.184E-03	5.210E-04	1.545E+02	1.545E+02
4	4.000E+04	6.781E-05	6.815E-06	2.441E+01	2.441E+01
5	5.000E+04	3.059E-03	3.075E-04	1.394E+02	1.394E+02
6	6.000E+04	9.325E-06	9.372E-07	-1.650E+01	-1.650E+01
7	7.000E+04	1.951E-03	1.961E-04	-1.577E+02	-1.577E+02
8	8.000E+04	6.078E-05	6.109E-06	-2.101E+01	-2.100E+01
9	9.000E+04	1.086E-02	1.091E-03	-1.996E+01	-1.996E+01

TOTAL HARMONIC DISTORTION = 1.270E-01 PERCENT

5.2

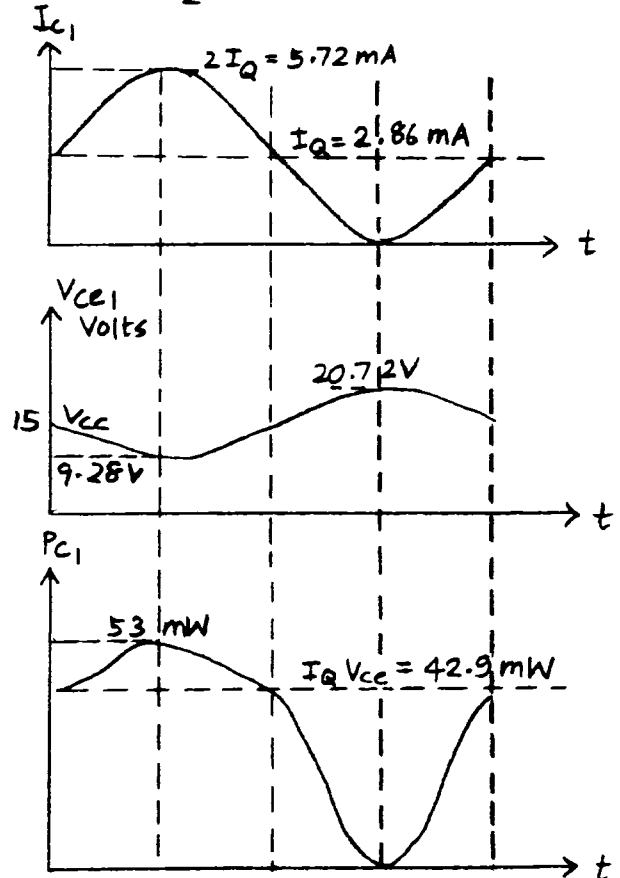
(a)



(b) $R_L = 2 \text{ k}\Omega$

$$\hat{V}_{om} = 5.72 \text{ V}, \hat{I}_{om} = 2.86 \text{ mA}$$

$$P_{L \text{ max}} = \frac{1}{2} \times 5.72 \times 2.86 \text{ mW} = 8.2 \text{ mW}$$

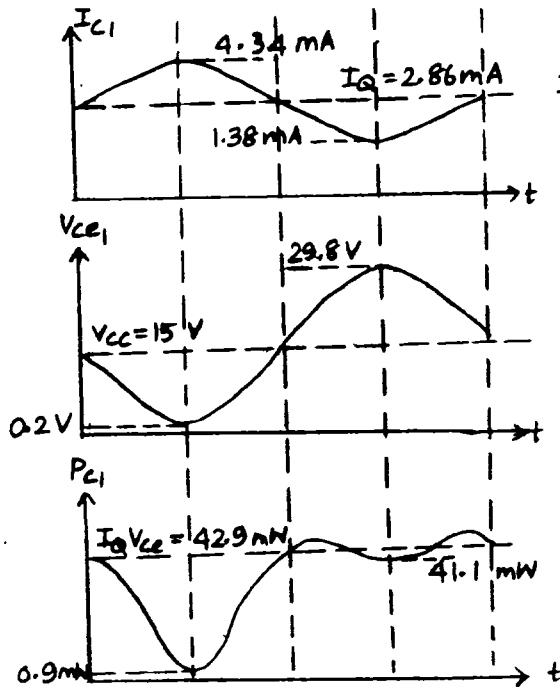


$$R_L = 10 \text{ k}\Omega$$

$$\hat{V}_{om} = V_{CC} - V_{CE} = 14.8 \text{ V}$$

$$\hat{I}_{om} = \frac{\hat{V}_{om}}{R_L} = \frac{14.8}{10} = 1.48 \text{ mA}$$

$$\therefore P_L|_{\max} = \frac{1}{2} \times 14.8 \times 1.48 = 11.0 \text{ mW}$$



$$(c) R_L = 2 \text{ k}\Omega$$

$$\eta = \frac{P_L}{P_{\text{SUPPLY}}} = \frac{8.2}{2 \times 42.9} = 9.6\%$$

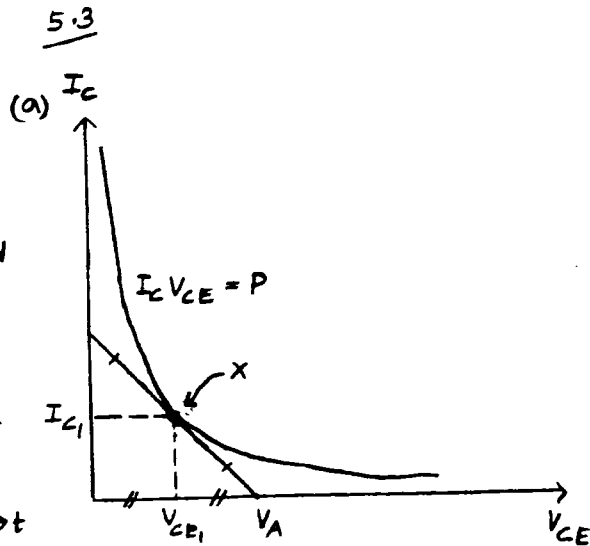
$$R_L = 10 \text{ k}\Omega$$

$$\eta_c = \frac{11}{2 \times 42.9} = 12.8\%$$

(d) For maximum efficiency,

$$R_L = \frac{V_{CC} - V_{CE(\text{sat})}}{I_Q} = \frac{14.8}{2.86} \text{ k}\Omega = 5.17 \text{ k}\Omega$$

$$P_L = \frac{1}{2} \frac{\hat{V}_{om}^2}{R_L} = \frac{1}{2} \frac{(14.8)^2}{5.18} \text{ mW} = 21.1 \text{ mW}$$



At any point the slope of the hyperbola is

$$\frac{dI_C}{dV_{CE}} = \frac{d}{dV_{CE}} \frac{P}{V_{CE}} = -\frac{P}{V_{CE}^2} = -\frac{I_C}{V_{CE}}$$

$$\text{At } X, \frac{dI_C}{dV_{CE}} = -\frac{I_{C1}}{V_{CE1}}$$

The slope of the tangent is thus $-\frac{I_C}{V_{CE}}$, and thus

$$-\frac{I_C}{V_A - V_{CE1}} = -\frac{I_{C1}}{V_{CE1}}$$

$$\therefore V_A = 2V_{CE1}$$

$\therefore X$ is the midpoint of the tangent.

(b) Maximum dissipation occurs at midpoint of the load line

$R_L = 2 \text{ k}\Omega$. Midpoint is where

$$V_{CE1} = \frac{20.7}{2} = 10.35 \text{ V}$$

corresponding current is

$$I_{C1} = \frac{10.35 \text{ V}}{2 \text{ k}\Omega} = 5.18 \text{ mA}$$

$$\therefore P_{C1}|_{\max} = 10.35 \times 5.18 = 53.6 \text{ mW}$$

$$R_L = 10 \text{ k}\Omega$$

Mid-point is where

$$V_{ce1} = \frac{1}{2} (15 + 2.86 \times 10) = 21.8 \text{ V}$$

corresponding current is

$$I_{c1} = 2.86 - \frac{21.8 - 15}{10} = 2.18 \text{ mA}$$

$$\therefore P_{c1}|_{\text{MAX}} = 21.8 \times 2.18 = 47.5 \text{ mW}$$

(c) since V_{cc} is constant, the average power drawn from the supplies is independent of signal level and equals $2V_{cc}I_Q$.

Thus, average power dissipated in Q_1 + average power dissipated in $R_L = V_{cc}I_Q$. Thus, the average power in $Q_1 = V_{cc}I_Q - \frac{1}{2} \frac{\hat{V}_{om}^2}{R_L} = P_{av}$

$$R_L = 2 \text{ k}\Omega$$

$$P_{av} = 42.9 - 8.2 = 34.7 \text{ mW}$$

$$R_L = 10 \text{ k}\Omega$$

$$P_{av} = 42.9 - 11 = 31.9 \text{ mW}$$

5.4

$$R_L = 2 \text{ k}\Omega$$

$$\hat{I}_{om} = 2.86 \text{ mA}, \hat{V}_{om} = 5.72 \text{ V}$$

$\therefore$ base current of Q_1 has a peak signal value $= \frac{1}{\beta} \hat{I}_{om} = 0.0286 \text{ mA}$

Since voltage gain is unity, peak input voltage $= \hat{V}_{om}$

$\therefore$ average signal power delivered is

$$P_i = \frac{1}{2} \times 0.0286 \times 5.72 \text{ mW}$$

$$\therefore P_i = 0.082 \text{ mW}$$

$$\therefore \text{Power gain} = \frac{P_L|_{\text{MAX}}}{P_i} = \frac{8.2}{0.082} = 100$$

$$R_L = 10 \text{ k}\Omega$$

$$\frac{1}{\beta} \hat{I}_{om} = \frac{1.48}{100} = 0.0148 \text{ mA}$$

$$\hat{V}_{om} = 14.8 \text{ V}$$

$$\therefore P_i = \frac{1}{2} \times 0.0148 \times 14.8 = 0.11 \text{ mW}$$

$$\text{Power gain} = \frac{11}{0.11} = 100$$

5.5

$$\hat{V}_o = 1 \text{ V}; \therefore \hat{I}_o = \frac{\hat{V}_{om}}{R_L} = \frac{1}{2} \text{ mA}$$

$$I_Q = 2.86 \text{ mA}$$

Quiescent

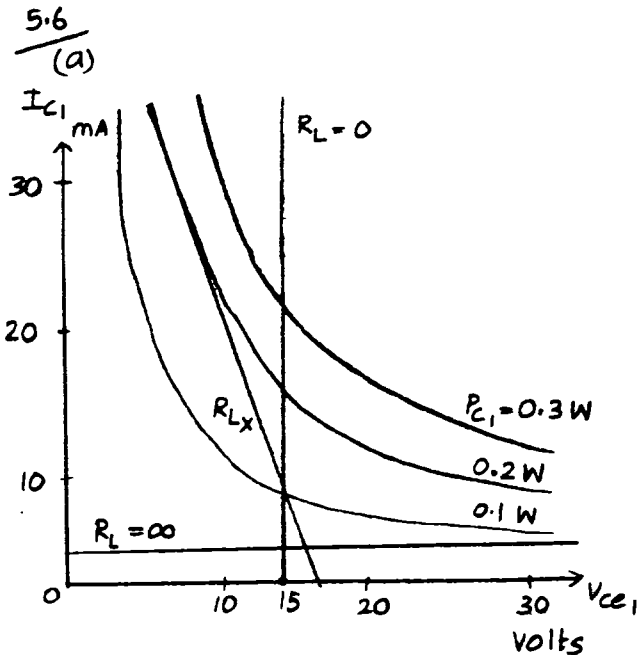
$$A_{VQ} = \frac{R_L}{R_L + \frac{1}{g_m}} = \frac{2000}{2000 + 9.1} = 0.9955$$

$$V_o = 1 \text{ V} \quad I_c = 3.36 \text{ mA}$$

$$A_V = \frac{2000}{2000 + 7.7} = 0.9962$$

$$V_o = -1 \text{ V} \quad I_c = 2.36 \text{ mA}$$

$$A_V = \frac{2000}{2000 + 11} = 0.9945$$



For $R_L = 0$, $I_{C1}|_{\text{MAX}} = \beta I_{B1} = 100 \times 0.3 = 30 \text{ mA}$

$$\therefore P_{C1}|_{\text{MAX}} = 30 \times 15 = 450 \text{ mW}$$

$R_L = \infty$ has max. value of P_{C1} of approx. 0.1 W at $V_{CE1} = 30 \text{ V}$

(b) From the graph $R_L = R_{Lx}$ is the minimum value of R_L for $P_{C1} < 0.2 \text{ W}$. This has a value

$$R_{Lx} \cong 310 \Omega$$

5.7

$$A_V = \frac{g_m}{g_m + g_{mb}} = \frac{1}{1 + X}$$

$$\text{From (1.200), } X = \frac{\gamma}{2\sqrt{2\phi_f + V_{SB}}}$$

(a) When $V_i = \text{max}$

From (5.62),

$$V_0 = -3.1 + (-0.25 + \sqrt{0.25^2 + 0.5 - 0.8 + 0.5\sqrt{0.6 + 3.1}})^2$$

$$= -0.68906 \text{ V}$$

$$V_{SB} = -0.68906 + 2.5 = 1.81094 \text{ V}$$

$$X^+ = \frac{0.5}{2\sqrt{0.6 + 1.81094}} = 0.16101$$

$$A_V^+ = \frac{1}{1 + 0.16101} = 0.86132$$

(b) When $V_i = 0$,

From (5.62),

$$V_0 = -3.1 + (-0.25 + \sqrt{0.25^2 - 0.8 + 0.5\sqrt{0.6 + 3.1}})^2 = -1.11683 \text{ V}$$

$$V_{SB} = -1.11683 + 2.5 = 1.38317 \text{ V}$$

$$X_Q = \frac{0.5}{2\sqrt{0.6 + 1.38317}} = 0.17753$$

$$A_{VQ} = \frac{1}{1 + 0.17753} = 0.84923$$

(c) When $V_i = \text{min}$

From (5.62),

$$V_0 = -3.1 + (-0.25 + \sqrt{0.25^2 - 0.5 - 0.8 + 0.5\sqrt{0.6 + 3.1}})^2 = -1.53767 \text{ V}$$

$$V_{SB} = -1.53767 + 2.5 = 0.96233 \text{ V}$$

$$X^- = \frac{0.5}{2\sqrt{0.6 + 0.96233}} = 0.20001$$

$$A_V^- = \frac{1}{1 + 0.20001} = 0.83333$$

5-8

$$(a) v_0 = a_1 v_i + a_2 v_i^2 + a_3 v_i^3 + \dots$$

$$A_v = \frac{dv_0}{dv_i} = a_1 + 2a_2 v_i + 3a_3 v_i^2 + \dots$$

$$(b) \text{ Let } v_i = \hat{v}_i \sin \omega t$$

$$A_v^+ = a_1 + 2a_2 \hat{v}_i + 3a_3 \hat{v}_i^2 + \dots$$

$$A_{v_Q} = a_1$$

$$A_v^- = a_1 - 2a_2 \hat{v}_i + 3a_3 \hat{v}_i^2$$

$$(c) E^+ = \frac{A_v^+ - A_{v_Q}}{A_{v_Q}} = \frac{2a_2 \hat{v}_i + 3a_3 \hat{v}_i^2}{a_1}$$

$$E^- = \frac{A_v^- - A_{v_Q}}{A_{v_Q}} = \frac{-2a_2 \hat{v}_i + 3a_3 \hat{v}_i^2}{a_1}$$

$$E^+ + E^- = \frac{6a_3 \hat{v}_i^2}{a_1}$$

$$E^+ - E^- = \frac{4a_2 \hat{v}_i}{a_1}$$

$$(d) \text{ From (5.54), } H_{D_2} = \frac{1}{2} \frac{a_2}{a_1} \hat{v}_i = \frac{E^+ - E^-}{8}$$

$$\text{From (5.57), } H_{D_3} = \frac{1}{4} \frac{a_3}{a_1} \hat{v}_i^2 = \frac{E^+ + E^-}{24}$$

$$(e) E^+ = \frac{A_v^+ - A_{v_Q}}{A_{v_Q}} = \frac{0.86132 - 0.84923}{0.84923} = 0.01423$$

$$E^- = \frac{A_v^- - A_{v_Q}}{A_{v_Q}} = \frac{0.83333 - 0.84923}{0.84923} = -0.01872$$

$$H_{D_2} = \frac{E^+ - E^-}{8} = \frac{0.01423 + 0.01872}{8} = 0.00412$$

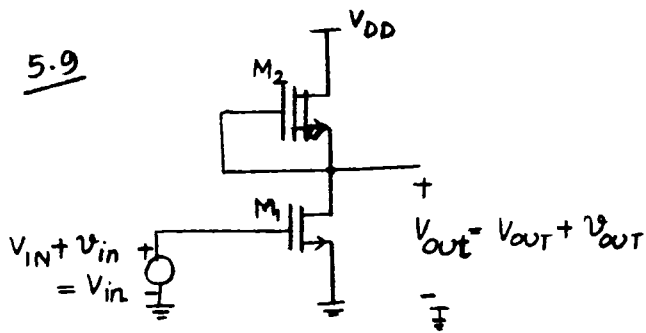
$$H_{D_3} = \frac{E^+ + E^-}{24} = \frac{0.01423 - 0.01872}{24} = -1.87 \times 10^{-4}$$

Example gives,

$$H_{D_2} = 0.0040$$

$$H_{D_3} = -1.8 \times 10^{-4}$$

5.9



$$I_{d_2} = I_{D_2} + i_{d_2} = f(V_{out})$$

$$= \frac{\kappa'}{2} \left(\frac{W}{L} \right)_2 \left[V_{t_0}(m_2) + \gamma \left(\sqrt{V_{out} + 2\phi_f} - \sqrt{2\phi_f} \right) \right]^2$$

$$f'(V_{out}) = \kappa' \left(\frac{W}{L} \right)_2 \left[V_{t_0}(m_2) + \gamma \left(\sqrt{V_{out} + 2\phi_f} - \sqrt{2\phi_f} \right) \right] \cdot \frac{\gamma}{2} (V_{out} + 2\phi_f)^{-1/2}$$

$$f''(V_{out}) = \kappa' \left(\frac{W}{L} \right)_2 \left[V_{t_0}(m_2) + \gamma \left(\sqrt{V_{out} + 2\phi_f} - \sqrt{2\phi_f} \right) \right] \cdot \left(-\frac{\gamma}{4} \right) (V_{out} + 2\phi_f)^{-3/2} + \frac{\gamma}{2} (V_{out} + 2\phi_f)^{-1/2} \cdot \kappa' \left(\frac{W}{L} \right)_2 \frac{\gamma}{2} (V_{out} + 2\phi_f)^{-1/2}$$

$$I_{d_2} = B_0 + B_1 v_{out} + B_2 v_{out}^2 + \dots$$

$$B_0 = f(V_{out} = V_{OUT})$$

$$= \frac{\kappa'}{2} \left(\frac{W}{L} \right)_2 \left[V_{t_0}(m_2) + \gamma \left(\sqrt{V_{OUT} + 2\phi_f} - \sqrt{2\phi_f} \right) \right]^2 = I_Q$$

$$B_1 = f'(V_{out} = V_{OUT})$$

$$= \sqrt{\frac{\kappa'}{2} \left(\frac{W}{L} \right)_2} \left[V_{t_0}(m_2) + \gamma \left(\sqrt{V_{OUT} + 2\phi_f} - \sqrt{2\phi_f} \right) \right] \times \sqrt{\frac{\kappa'}{2} \left(\frac{W}{L} \right)_2} \gamma (V_{OUT} + 2\phi_f)^{-1/2}$$

$$= \sqrt{I_Q} \sqrt{\frac{\kappa'}{2} \left(\frac{W}{L} \right)_2} \gamma (V_{OUT} + 2\phi_f)^{-1/2}$$

$$B_2 = \frac{f''(V_{out} = V_{OUT})}{2!}$$

$$B_2 = \frac{\kappa'}{2} \left(\frac{W}{L} \right)_2 \left[V_{t_0}(m_2) + \gamma \left(\sqrt{V_{OUT} + 2\phi_f} - \sqrt{2\phi_f} \right) \right] \cdot \left(-\frac{\gamma}{4} \right) (V_{OUT} + 2\phi_f)^{-3/2} + \frac{\gamma}{2} (V_{OUT} + 2\phi_f)^{-1/2}$$

$$\cdot \kappa' \left(\frac{W}{L} \right)_2 \left(\frac{\gamma}{2} \right) (V_{OUT} + 2\phi_f)^{-1/2}$$

$$B_2 = \sqrt{\frac{\kappa'}{2} \left(\frac{W}{L} \right)_2} \left[V_{t_0}(m_2) + \gamma \left(\sqrt{V_{OUT} + 2\phi_f} - \sqrt{2\phi_f} \right) \right] \cdot \sqrt{\frac{\kappa'}{2} \left(\frac{W}{L} \right)_2} \left(-\frac{\gamma}{4} \right) (V_{OUT} + 2\phi_f)^{-3/2}$$

$$+ \frac{\gamma^2}{4} \frac{\kappa'}{2} \left(\frac{W}{L} \right)_2 (V_{OUT} + 2\phi_f)^{-1}$$

$$B_2 = -\sqrt{I_Q} \sqrt{\frac{\kappa'}{2} \left(\frac{W}{L} \right)_2} \frac{\gamma}{4} (V_{OUT} + 2\phi_f)^{-3/2} + \frac{\gamma^2}{4} \frac{\kappa'}{2} \left(\frac{W}{L} \right)_2 (V_{OUT} + 2\phi_f)^{-1}$$

$$I_{d_2} = I_{D_2} + i_{d_2} = B_0 + B_1 v_{out} + B_2 v_{out}^2 + \dots$$

$$\text{But, } I_{D_2} = B_0 = I_Q$$

$$\text{So, } i_{d_1} = i_{d_2} = B_1 v_{out} + B_2 v_{out}^2 + \dots$$

Invert,

$$v_{out} = b_1 i_{d_2} + b_2 i_{d_2}^2 + \dots \text{ and } i_{d_2} = i_{d_1}$$

$$v_{out} = b_1 i_{d_1} + b_2 i_{d_1}^2 + \dots$$

Find i_{d_1}

$$I_{d_1} = I_{D_1} + i_{d_1} = \frac{\kappa'}{2} \left(\frac{W}{L} \right)_1 (V_{IN} + v_{in} - V_{t_0}(m_1))^2$$

$$i_{d_1} = \frac{\kappa'}{2} \left(\frac{W}{L} \right)_1 \left[(V_{IN} - V_{t_0}(m_1))^2 + v_{in}^2 + 2(V_{IN} - V_{t_0}(m_1))v_{in} - (V_{IN} - V_{t_0}(m_1))^2 \right]$$

$$= \frac{\kappa'}{2} \left(\frac{W}{L} \right)_1 \left[v_{in}^2 + 2(V_{IN} - V_{t_0}(m_1))v_{in} \right]$$

$$v_{out} = b_1 i_{d1} + b_2 i_{d1}^2 + \dots$$

$$v_{out} = b_1 \left\{ \frac{k'}{2} \left(\frac{W}{L} \right)_1 [v_{in}^2 + 2(V_{IN} - V_{to(m1)}) v_{in}] \right\}$$

$$+ b_2 \left\{ \frac{k'}{2} \left(\frac{W}{L} \right)_1 [v_{in}^2 + 2(V_{IN} - V_{to(m1)}) v_{in}] \right\} + \dots + \left\{ \sqrt{I_Q} \sqrt{\frac{k'}{2} \left(\frac{W}{L} \right)_2} \frac{\gamma}{4} (v_{out} + 2\phi_f)^{\frac{3}{2}} - \frac{\gamma^2 k'}{4} \left(\frac{W}{L} \right)_2 (v_{out} + 2\phi_f)^{\frac{1}{2}} \right\}$$

$$v_{out} = b_1 \frac{k'}{2} \left(\frac{W}{L} \right)_1 2(V_{IN} - V_{to(m1)}) v_{in}$$

$$+ b_1 \frac{k'}{2} \left(\frac{W}{L} \right)_1 v_{in}^2 + b_2 \left[\frac{k'}{2} \left(\frac{W}{L} \right)_1 \right]^2 4(V_{IN} - V_{to(m1)})^2 v_{in}^2$$

+ ...

$$v_{out} = a_1 v_{in} + a_2 v_{in}^2 + \dots$$

$$a_1 = b_1 \frac{k'}{2} \left(\frac{W}{L} \right)_1 2(V_{IN} - V_{to(m1)})$$

$$a_2 = b_1 \frac{k'}{2} \left(\frac{W}{L} \right)_1 + b_2 \left[\frac{k'}{2} \left(\frac{W}{L} \right)_1 \right]^2 4(V_{IN} - V_{to(m1)})^2$$

From (5.46), $b_1 = \frac{1}{B_1}$

$$a_1 = \frac{\frac{k'}{2} \left(\frac{W}{L} \right)_1 2(V_{IN} - V_{to(m1)})}{B_1} = \frac{\frac{k'}{2} \left(\frac{W}{L} \right)_1 2(V_{IN} - V_{to(m1)})}{\sqrt{I_Q} \sqrt{\frac{k'}{2} \left(\frac{W}{L} \right)_2} \gamma (v_{out} + 2\phi_f)^{\frac{3}{2}}}$$

$$a_1 = \frac{\sqrt{\frac{k'}{2} \left(\frac{W}{L} \right)_2} 2 \sqrt{\frac{k'}{2} \left(\frac{W}{L} \right)_1} (V_{IN} - V_{to(m1)})}{\sqrt{I_Q} \sqrt{\frac{k'}{2} \left(\frac{W}{L} \right)_2} \gamma (v_{out} + 2\phi_f)^{\frac{3}{2}}}$$

Since $\sqrt{I_Q} = \sqrt{\frac{k'}{2} \left(\frac{W}{L} \right)_1} (V_{IN} - V_{to(m1)})$

$$a_1 = \frac{2}{\gamma} \sqrt{\frac{(W/L)_1}{(W/L)_2}} (v_{out} + 2\phi_f)^{\frac{1}{2}}$$

$$a_2 = b_1 \frac{k'}{2} \left(\frac{W}{L} \right)_1 + b_2 \left[\frac{k'}{2} \left(\frac{W}{L} \right)_1 \right]^2 4(V_{IN} - V_{to(m1)})^2$$

From (5.47), $b_2 = -\frac{B_2}{B_1^3}$

$$a_2 = \frac{\frac{k'}{2} \left(\frac{W}{L} \right)_1}{B_1} - \frac{B_2}{B_1^3} \frac{k'}{2} \left(\frac{W}{L} \right)_1 \frac{k'}{2} \left(\frac{W}{L} \right)_1 (V_{IN} - V_{to(m1)})^2 4$$

$$a_2 = \frac{\frac{k'}{2} \left(\frac{W}{L} \right)_1}{B_1} - \frac{B_2}{B_1^3} \frac{k'}{2} \left(\frac{W}{L} \right)_1 4 I_Q$$

$$a_2 = \frac{\frac{k'}{2} \left(\frac{W}{L} \right)_1}{\sqrt{I_Q} \sqrt{\frac{k'}{2} \left(\frac{W}{L} \right)_2} \gamma (v_{out} + 2\phi_f)^{\frac{1}{2}}}$$

$$+ \frac{\left(\frac{W}{L} \right)_1 \left(\frac{W}{L} \right)_2 \gamma^2 - \frac{k'}{2} \left(\frac{W}{L} \right)_1}{\sqrt{I_Q} \sqrt{\frac{k'}{2} \left(\frac{W}{L} \right)_2} \gamma (v_{out} + 2\phi_f)^{\frac{1}{2}}}$$

$$= \frac{\frac{k'}{2} \left(\frac{W}{L} \right)_1}{\sqrt{I_Q} \sqrt{\frac{k'}{2} \left(\frac{W}{L} \right)_2} \gamma (v_{out} + 2\phi_f)^{\frac{1}{2}}}$$

$$\cdot \frac{k'}{2} \left(\frac{W}{L} \right)_1 4 I_Q$$

$$a_2 = \frac{\frac{k'}{2} \left(\frac{W}{L} \right)_1}{\sqrt{I_Q} \sqrt{\frac{k'}{2} \left(\frac{W}{L} \right)_2} \gamma (v_{out} + 2\phi_f)^{\frac{1}{2}}}$$

$$+ \left(\frac{W}{L} \right)_1 \left(\frac{W}{L} \right)_2 \gamma^2 - \frac{k'}{2} \left(\frac{W}{L} \right)_1}{\sqrt{I_Q} \sqrt{\frac{k'}{2} \left(\frac{W}{L} \right)_2} \gamma (v_{out} + 2\phi_f)^{\frac{1}{2}}}$$

$$a_2 = \frac{(W/L)_1}{(W/L)_2 \gamma^2}$$

From (5.54),

$$HD_2 = \frac{1}{2} \frac{a_2}{a_1} \hat{v}_i$$

$$HD_2 = \frac{1}{2} \frac{(W/L)_1}{(W/L)_2 \gamma^2} \hat{v}_i$$

$$\frac{2}{\gamma} \sqrt{\frac{(W/L)_1}{(W/L)_2}} \sqrt{v_{out} + 2\phi_f}$$

$$HD_2 = \frac{1}{4} \sqrt{\frac{(W/L)_1}{(W/L)_2}} \frac{1}{\gamma} \frac{1}{\sqrt{v_{out} + 2\phi_f}} \hat{v}_i$$

$$= \frac{1}{4} \sqrt{\frac{100}{100}} \frac{1}{0.5} \frac{1}{\sqrt{1+2(0.3)}} (0.01)$$

$$\cong 0.4\%$$

HD2 FOR COMMON-SOURCE AMPLIFIER WITH DEPLETION LOAD

```

VDD      100      0      3
M1       2       1       0      0      CMOS1 W=100U L=1U
M2      100      2       2       0      CMOS2 W=100U L=1U
.MODEL CMOS1 NMOS LEVEL=1 LAMBDA=0M VTO=0.6
+ GAMMA=0.5 PHI=0.6 KP=200U
.MODEL CMOS2 NMOS LEVEL=1 LAMBDA=0M VTO=-0.6
+ GAMMA=0.5 PHI=0.6 KP=200U
VIN       1       3       SIN      (0      0.01      1K)
VINDC     3       0       0.9548
* THE DC INPUT IS ADJUSTED BY TRIAL AND ERROR
* UNTIL THE DC OUTPUT = 1 VOLT
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.TR      100U      2M
.PLOT    TRAN      V(2)
.FOUR     1K      V(2)
.END

```

```

**** OPERATING POINT INFORMATION      THOM= 27.000 TEMP= 27.000
NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:1      = 9.548E-01 0:2      = 1.000E+00 0:3      = 9.548E-01
+0:100     = 3.000E+00

```

**** MOSFETS

SUBCKT

```

ELEMENT 0:M1      0:M2
MODEL   0:CMOS1  0:CMOS2
ID      1.259E-03 1.259E-03
IBS     0.        -1.000E-14
IED     -1.000E-14 -3.000E-14
VGS     9.548E-01 0.
VDS     1.000E+00 1.999E+00
VBS     0.        -1.000E+00
VTH     6.000E-01 -3.548E-01
VDSAT   3.548E-01 3.548E-01
BETA    2.000E-02 2.000E-02
GAM EFF 5.000E-01 5.000E-01
GM       7.096E-03 7.096E-03
GDS      0.        0.
GMB      2.290E-03 1.402E-03

```

***** TRANSIENT ANALYSIS THOM= 27.000 TEMP= 27.000

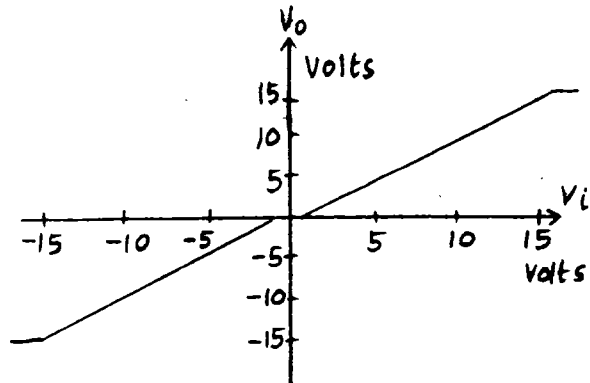
TIME	V(2)
0.	1.00E+00
1.00E-04	9.71E-01
2.00E-04	9.53E-01
3.00E-04	9.53E-01
4.00E-04	9.71E-01
5.00E-04	1.00E+00
6.00E-04	1.03E+00
7.00E-04	1.04E+00
8.00E-04	1.04E+00
9.00E-04	1.03E+00
1.00E-03	1.00E+00
1.10E-03	9.71E-01
1.20E-03	9.53E-01
1.30E-03	9.53E-01
1.40E-03	9.71E-01
1.50E-03	1.00E+00
1.60E-03	1.03E+00
1.70E-03	1.04E+00
1.80E-03	1.04E+00
1.90E-03	1.03E+00
2.00E-03	1.00E+00

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(2)

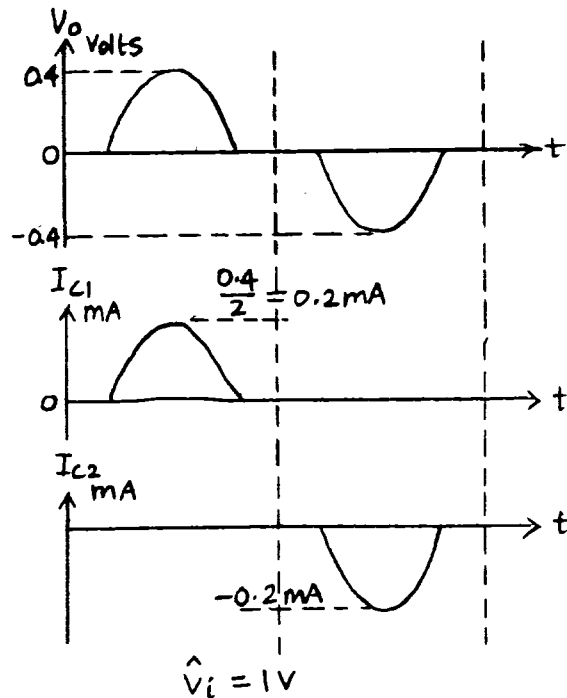
DC COMPONENT = 1.000D+00

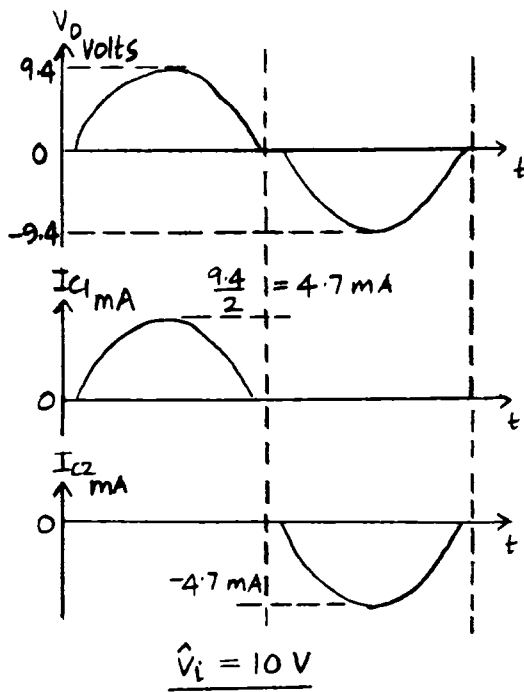
HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	1.000E+03	5.038E-02	1.000E+00	1.800E+02	0.
2	2.000E+03	1.966E-04	3.903E-03	-9.135E+01	-2.713E+02
3	3.000E+03	8.333E-06	1.654E-04	-7.803E+01	-2.580E+02
4	4.000E+03	5.605E-07	1.113E-05	-1.465E+02	-3.265E+02
5	5.000E+03	1.724E-05	3.422E-04	-3.464E+01	-2.146E+02
6	6.000E+03	6.125E-07	1.216E-05	-1.233E+02	-3.033E+02
7	7.000E+03	1.065E-05	2.115E-04	-6.563E+00	-1.865E+02
8	8.000E+03	2.798E-07	5.554E-06	1.587E+02	-2.120E+01
9	9.000E+03	4.674E-05	9.278E-04	1.490E+02	-3.096E+01

TOTAL HARMONIC DISTORTION = 4.035E-01 PERCENT

5.10
(a)

(b)





CLASS-B OUTPUT STAGE (PEAK INPUT AMPLITUDE = 1 V)

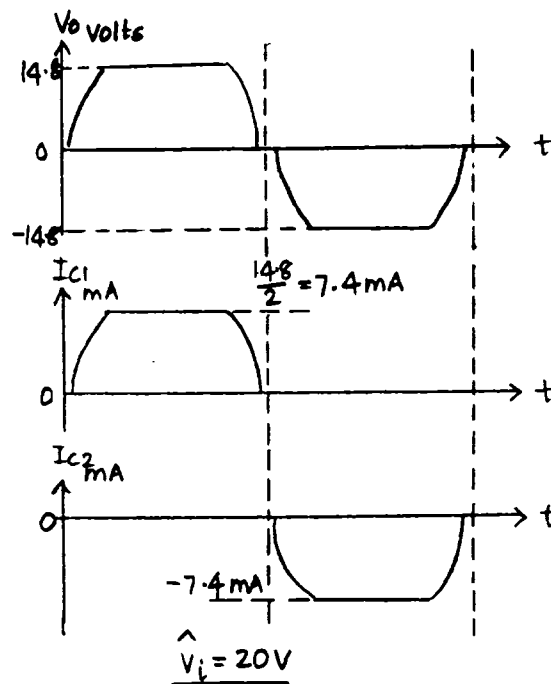
```

VCC 100 0 15
VEE 200 0 -15
Q1 100 1 2 NPN
Q2 200 1 2 PNP
RL 2 0 2K
.MODEL NPN NPN RB=100 BF=100 IS=1E-16 RC=20 VAF=130
.MODEL PNP PNP RB=100 BF=100 IS=1E-16 RC=20 VAF=50
VIN 1 0 SIN 0 1 10K 0 0
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.DC VIN -15 15 0.5
.PLOT DC V(2)
.TR 4U 200U
.PLOT TRAN V(2)
.FOUR 10K V(2)
.END

```

***** DC TRANSFER CURVES THOM= 27.000 TEMP= 27.000

VOLT	V(2)								
(A)		-2.000E+01	-1.000E+01	0.	1.000E+01	2.000E+01			
-1.500E+01	-1.41E+01	+	+	+	+	+	+	+	+
-1.450E+01	-1.36E+01	+	A	+	+	+	+	+	+
-1.400E+01	-1.31E+01	+	A	+	+	+	+	+	+
-1.350E+01	-1.26E+01	+	A	+	+	+	+	+	+
-1.300E+01	-1.21E+01	+	A	+	+	+	+	+	+
-1.250E+01	-1.16E+01	+	A	+	+	+	+	+	+
-1.200E+01	-1.11E+01	+	A	+	+	+	+	+	+
-1.150E+01	-1.06E+01	+	A	+	+	+	+	+	+
-1.100E+01	-1.01E+01	+	A	+	+	+	+	+	+
-1.050E+01	-9.68E+00	+	A	+	+	+	+	+	+
-1.000E+01	-9.18E+00	+	A	+	+	+	+	+	+
-9.500E+00	-8.68E+00	+	A	+	+	+	+	+	+
-9.000E+00	-8.18E+00	+	A	+	+	+	+	+	+
-8.500E+00	-7.69E+00	+	A	+	+	+	+	+	+
-8.000E+00	-7.19E+00	+	A	+	+	+	+	+	+
-7.500E+00	-6.69E+00	+	A	+	+	+	+	+	+
-7.000E+00	-6.19E+00	+	A	+	+	+	+	+	+
-6.500E+00	-5.70E+00	+	A	+	+	+	+	+	+
-6.000E+00	-5.20E+00	+	A	+	+	+	+	+	+
-5.500E+00	-4.70E+00	+	A	+	+	+	+	+	+
-5.000E+00	-4.21E+00	+	A	+	+	+	+	+	+
-4.500E+00	-3.71E+00	+	A	+	+	+	+	+	+
-4.000E+00	-3.21E+00	+	A	+	+	+	+	+	+
-3.500E+00	-2.72E+00	+	A	+	+	+	+	+	+
-3.000E+00	-2.22E+00	+	A	+	+	+	+	+	+
-2.500E+00	-1.73E+00	+	A	+	+	+	+	+	+
-2.000E+00	-1.24E+00	+	A	+	+	+	+	+	+
-1.500E+00	-7.57E-01	+	A	+	+	+	+	+	+
-1.000E+00	-2.83E-01	+	A	+	+	+	+	+	+
-5.000E-01	-6.45E-05	+	A	+	+	+	+	+	+
0.	0.	+	A	+	+	+	+	+	+
5.000E-01	5.57E-05	+	A	+	+	+	+	+	+
1.000E+00	2.79E-01	+	A	+	+	+	+	+	+
1.500E+00	7.53E-01	+	A	+	+	+	+	+	+
2.000E+00	1.24E+00	+	A	+	+	+	+	+	+
2.500E+00	1.73E+00	+	A	+	+	+	+	+	+
3.000E+00	2.22E+00	+	A	+	+	+	+	+	+
3.500E+00	2.71E+00	+	A	+	+	+	+	+	+
4.000E+00	3.21E+00	+	A	+	+	+	+	+	+
4.500E+00	3.71E+00	+	A	+	+	+	+	+	+
5.000E+00	4.20E+00	+	A	+	+	+	+	+	+
5.500E+00	4.70E+00	+	A	+	+	+	+	+	+
6.000E+00	5.20E+00	+	A	+	+	+	+	+	+
6.500E+00	5.69E+00	+	A	+	+	+	+	+	+
7.000E+00	6.19E+00	+	A	+	+	+	+	+	+
7.500E+00	6.69E+00	+	A	+	+	+	+	+	+
8.000E+00	7.19E+00	+	A	+	+	+	+	+	+
8.500E+00	7.68E+00	+	A	+	+	+	+	+	+
9.000E+00	8.18E+00	+	A	+	+	+	+	+	+
9.500E+00	8.68E+00	+	A	+	+	+	+	+	+
1.000E+01	9.18E+00	+	A	+	+	+	+	+	+
1.050E+01	9.68E+00	+	A	+	+	+	+	+	+
1.100E+01	1.01E+01	+	A	+	+	+	+	+	+
1.150E+01	1.06E+01	+	A	+	+	+	+	+	+
1.200E+01	1.11E+01	+	A	+	+	+	+	+	+
1.250E+01	1.16E+01	+	A	+	+	+	+	+	+
1.300E+01	1.21E+01	+	A	+	+	+	+	+	+
1.350E+01	1.26E+01	+	A	+	+	+	+	+	+
1.400E+01	1.31E+01	+	A	+	+	+	+	+	+
1.450E+01	1.36E+01	+	A	+	+	+	+	+	+
1.500E+01	1.41E+01	+	A	+	+	+	+	+	+



***** TRANSIENT ANALYSIS THOM= 27.000 TEMP= 27.000

TIME	V(2)
0.	0.
4.000E-06	0.
8.000E-06	2.75E-05
1.200E-05	2.58E-02
1.600E-05	1.41E-01
2.000E-05	2.29E-01
2.400E-05	2.74E-01
2.800E-05	2.63E-01
3.200E-05	1.94E-01
3.600E-05	8.18E-02
4.000E-05	1.29E-02
4.400E-05	1.38E-05
4.800E-05	0.
5.200E-05	0.
5.600E-05	-2.75E-06
6.000E-05	-6.89E-03
6.400E-05	-8.87E-02
6.800E-05	-1.97E-01
7.200E-05	-2.67E-01
7.600E-05	-2.81E-01
8.000E-05	-2.32E-01
8.400E-05	-1.43E-01
8.800E-05	-2.77E-02
9.200E-05	-3.19E-05
9.600E-05	0.
1.000E-04	0.
1.040E-04	7.92E-07
1.080E-04	2.06E-03
1.120E-04	3.42E-02
1.160E-04	1.41E-01
1.200E-04	2.29E-01
1.240E-04	2.74E-01
1.280E-04	2.63E-01
1.320E-04	1.94E-01
1.360E-04	8.18E-02
1.400E-04	1.29E-02
1.440E-04	1.38E-05
1.480E-04	0.
1.520E-04	0.
1.560E-04	-2.75E-06
1.600E-04	-6.89E-03
1.640E-04	-8.87E-02
1.680E-04	-1.97E-01
1.720E-04	-2.67E-01
1.760E-04	-2.81E-01
1.800E-04	-2.32E-01
1.840E-04	-1.43E-01
1.880E-04	-2.77E-02
1.920E-04	-3.19E-05
1.960E-04	0.
2.000E-04	0.

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(2)

DC COMPONENT = -8.789D-04

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	1.830E-01	1.000E+00	-4.672E-03	0.
2	2.000E+04	1.020E-03	5.575E-03	9.129E+01	9.129E+01
3	3.000E+04	9.341E-02	5.105E-01	-1.798E+02	-1.798E+02
4	4.000E+04	8.243E-05	4.505E-04	1.329E+02	1.329E+02
5	5.000E+04	1.125E-02	6.151E-02	1.156E+00	1.160E+00
6	6.000E+04	2.129E-04	1.164E-03	-8.186E+01	-8.186E+01
7	7.000E+04	9.939E-03	5.432E-02	4.287E+00	4.291E+00
8	8.000E+04	6.480E-05	3.542E-04	-4.752E+01	-4.752E+01
9	9.000E+04	8.940E-04	4.886E-03	-1.399E+02	-1.399E+02

TOTAL HARMONIC DISTORTION = 5.171E+01 PERCENT

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT

ELEMENT	0:Q1	0:Q2
MODEL	0:NPN	0:PNP
IB	-1.000E-16	1.000E-16
IC	2.115E-16	-2.300E-16
VBE	3.692E-14	3.692E-14
VCE	1.500E+01	-1.500E+01
VBC	-1.500E+01	1.500E+01
VS	-1.500E+01	1.500E+09
POWER	3.173E-15	3.450E-15

**** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:1	= 0.	0:2	=-3.692E-14	0:100	= 1.500E+01
+0:200	=-1.500E+01				

CLASS-B OUTPUT STAGE (PEAK INPUT AMPLITUDE = 10 V)

VCC	100	0	15
VBE	200	0	-15
Q1	100	1	2 NPN
Q2	200	1	2 PNP
RL	2	0	2K
.MODEL NPN NPN RB=100 BF=100 IS=1E-16 RC=20 VAF=130			
.MODEL PNP PNP RB=100 BF=100 IS=1E-16 RC=20 VAF=50			
VIN	1	0	SIN 0 10 10K 0 0
.OPTIONS NOPAGE NOMOD			
.WIDTH OUT=80			
.OP			
.TR	4U	200U	
.PLOT	TRAN	V(2)	
.FOUR	10K	V(2)	
.END			

***** TRANSIENT ANALYSIS THOM= 27.000 TEMP= 27.000

TIME	V(2)
0.	0.
4.000E-06	1.71E+00
8.000E-06	4.00E+00
1.200E-05	6.00E+00
1.600E-05	7.63E+00
2.000E-05	8.62E+00
2.400E-05	9.12E+00
2.800E-05	9.00E+00
3.200E-05	8.23E+00
3.600E-05	6.89E+00
4.000E-05	5.03E+00
4.400E-05	2.87E+00
4.800E-05	8.59E-01
5.200E-05	-5.75E-01
5.600E-05	-2.89E+00
6.000E-05	-5.06E+00
6.400E-05	-6.87E+00
6.800E-05	-8.23E+00
7.200E-05	-9.00E+00
7.600E-05	-9.16E+00
8.000E-05	-8.62E+00
8.400E-05	-7.60E+00
8.800E-05	-6.04E+00
9.200E-05	-4.02E+00
9.600E-05	-1.72E+00
1.000E-04	0.
1.040E-04	1.71E+00
1.080E-04	3.99E+00
1.120E-04	5.99E+00
1.160E-04	7.63E+00
1.200E-04	8.62E+00
1.240E-04	9.12E+00
1.280E-04	9.00E+00
1.320E-04	8.23E+00
1.360E-04	6.89E+00
1.400E-04	5.03E+00
1.440E-04	2.87E+00
1.480E-04	8.59E-01
1.520E-04	-5.75E-01
1.560E-04	-2.89E+00
1.600E-04	-5.06E+00
1.640E-04	-6.87E+00
1.680E-04	-8.23E+00
1.720E-04	-9.00E+00
1.760E-04	-9.16E+00
1.800E-04	-8.62E+00
1.840E-04	-7.60E+00
1.880E-04	-6.04E+00
1.920E-04	-4.02E+00
1.960E-04	-1.72E+00
2.000E-04	0.

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(2)

DC COMPONENT = -8.955D-04

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	8.945E+00	1.000E+00	-2.161E-01	0.
2	2.000E+04	6.121E-04	6.842E-05	7.039E+01	7.060E+01
3	3.000E+04	3.095E-01	3.459E-02	-1.744E+02	-1.742E+02
4	4.000E+04	1.480E-03	1.654E-04	1.171E+02	1.173E+02
5	5.000E+04	1.651E-01	1.845E-02	-1.708E+02	-1.706E+02
6	6.000E+04	1.231E-03	1.376E-04	1.133E+02	1.135E+02
7	7.000E+04	1.006E-01	1.125E-02	-1.663E+02	-1.661E+02
8	8.000E+04	8.272E-04	9.247E-05	1.224E+02	1.227E+02
9	9.000E+04	5.414E-02	6.052E-03	-1.558E+02	-1.556E+02

TOTAL HARMONIC DISTORTION = 4.123E+00 PERCENT

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

MODE	=VOLTAGE	MODE	=VOLTAGE	MODE	=VOLTAGE
+0:1	= 0.	0:2	=-3.692E-14	0:100	= 1.500E+01
+0:200	=-1.500E+01				

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT

ELEMENT	0:Q1	0:Q2
MODEL	0:NPN	0:PMP
IB	-1.000E-16	1.000E-16
IC	2.115E-16	-2.300E-16
VBE	3.692E-14	3.692E-14
VCE	1.500E+01	-1.500E+01
VBC	-1.500E+01	1.500E+01
VS	-1.500E+01	1.500E-09
POWER	3.173E-15	3.450E-15

CLASS-B OUTPUT STAGE (PEAK INPUT AMPLITUDE = 20 V)

```

VCC 100 0 15
VBE 200 0 -15
Q1 100 1 2 NPN
Q2 200 1 2 PNP
RL 2 0 2K
.MODEL NPN NPN RB=100 BF=100 IS=1E-16 RC=20 VAF=130
.MODEL PNP PNP RB=100 BF=100 IS=1E-16 RC=20 VAF=50
VIN 1 0 SIN 0 20 10K 0 0
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.TR 4U 200U
.PLOT TRAN V(2)
.FOUR 10K V(2)
.END

```

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

MODE	=VOLTAGE	MODE	=VOLTAGE	MODE	=VOLTAGE
+0:1	= 0.	0:2	=-3.692E-14	0:100	= 1.500E+01
+0:200	=-1.500E+01				

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT

ELEMENT	0:Q1	0:Q2
MODEL	0:NPN	0:PMP
IB	-1.000E-16	1.000E-16
IC	2.115E-16	-2.300E-16
VBE	3.692E-14	3.692E-14
VCE	1.500E+01	-1.500E+01
VBC	-1.500E+01	1.500E+01
VS	-1.500E+01	1.500E-09
POWER	3.173E-15	3.450E-15

***** TRANSIENT ANALYSIS TNOM= 27.000 TEMP= 27.000

TIME (A)	V(2)	-2.000E+01	-1.000E+01	0.	1.000E+01	2.000E+01
0.	0.	-	-	-	-	-
4.000E-06	4.18E+00	+	+	+	A+	+
8.000E-06	8.77E+00	+	+	+	+	A+
1.200E-05	1.28E+01	+	+	+	+	A+
1.600E-05	1.50E+01	+	+	+	+	A+
2.000E-05	1.53E+01	+	+	+	+	A+
2.400E-05	1.55E+01	+	+	+	+	A+
2.800E-05	1.55E+01	+	+	+	+	A+
3.200E-05	1.52E+01	+	+	+	+	A+
3.600E-05	1.45E+01	+	+	+	+	A+
4.000E-05	1.08E+01	-	-	-	-	-
4.400E-05	6.51E+00	+	+	+	+	A+
4.800E-05	1.97E+00	+	+	+	A+	+
5.200E-05	-1.74E+00	+	+	+	A+	+
5.600E-05	-6.55E+00	+	+	A+	+	+
6.000E-05	-1.09E+01	+	A+	+	+	+
6.400E-05	-1.45E+01	A+	+	+	+	+
6.800E-05	-1.52E+01	A+	+	+	+	+
7.200E-05	-1.54E+01	A+	+	+	+	+
7.600E-05	-1.55E+01	A+	+	+	+	+
8.000E-05	-1.53E+01	-	-	-	-	-
8.400E-05	-1.50E+01	A+	+	+	+	+
8.800E-05	-1.28E+01	+	A+	+	+	+
9.200E-05	-8.76E+00	+	+	A+	+	+
9.600E-05	-4.15E+00	+	+	A+	+	+
1.000E-04	0.	+	+	+	A+	+
1.040E-04	4.17E+00	+	+	+	A+	+
1.080E-04	8.74E+00	+	+	+	+	A+
1.120E-04	1.27E+01	+	+	+	+	A+
1.160E-04	1.50E+01	+	+	+	+	A+
1.200E-04	1.53E+01	-	-	-	-	-
1.240E-04	1.55E+01	+	+	+	+	+
1.280E-04	1.55E+01	+	+	+	+	+
1.320E-04	1.52E+01	+	+	+	+	+
1.360E-04	1.45E+01	+	+	+	+	A+
1.400E-04	1.08E+01	+	+	+	+	A+
1.440E-04	6.51E+00	+	+	+	+	A+
1.480E-04	1.97E+00	+	+	+	A+	+
1.520E-04	-1.74E+00	+	+	+	A+	+
1.560E-04	-6.55E+00	+	+	A+	+	+
1.600E-04	-1.09E+01	-	-	-	-	-
1.640E-04	-1.45E+01	A+	+	+	+	+
1.680E-04	-1.52E+01	A+	+	+	+	+
1.720E-04	-1.54E+01	A+	+	+	+	+
1.760E-04	-1.55E+01	A+	+	+	+	+
1.800E-04	-1.53E+01	A+	+	+	+	+
1.840E-04	-1.50E+01	A+	+	+	+	+
1.880E-04	-1.28E+01	+	A+	+	+	+
1.920E-04	-8.76E+00	+	+	A+	+	+
1.960E-04	-4.15E+00	+	+	A+	+	+
2.000E-04	0.	-	-	-	-	-

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(2)

DC COMPONENT = -1.246D-04

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	1.696E+01	1.000E+00	-1.072E-01	0.
2	2.000E+04	1.866E-03	1.100E-04	7.729E+00	7.836E+00
3	3.000E+04	9.753E-01	5.748E-02	-1.358E+00	-1.251E+00
4	4.000E+04	1.161E-03	6.840E-05	1.193E+02	1.194E+02
5	5.000E+04	6.865E-01	4.046E-02	-1.782E+02	-1.781E+02
6	6.000E+04	2.384E-03	1.405E-04	1.552E+02	1.553E+02
7	7.000E+04	1.539E-01	9.071E-03	-1.693E+02	-1.692E+02
8	8.000E+04	9.693E-04	5.713E-05	1.271E+02	1.272E+02
9	9.000E+04	9.105E-02	5.367E-03	-1.859E+01	-1.848E+01

TOTAL HARMONIC DISTORTION = 7.108E+00 PERCENT

5.11

$$\hat{V}_o = V_{CC} - V_{CE(sat.)} = 11.8 \text{ V}$$

$$I_{\text{supply}} = \frac{1}{\pi} \frac{\hat{V}_o}{R_L} = \frac{1}{\pi} \frac{11.8}{1} = 3.75 \text{ mA}$$

$$\text{Supply power} = P_{\text{supply}}$$

$$= I_{\text{supply}} \times 2V_{CC} = 3.75 \times 24 \text{ mW}$$

$$= 90.2 \text{ mW}$$

Power delivered to R_L

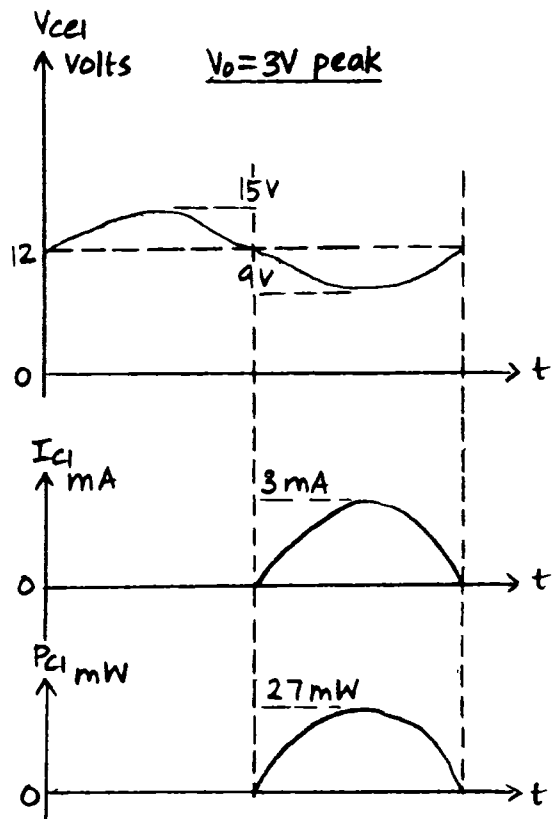
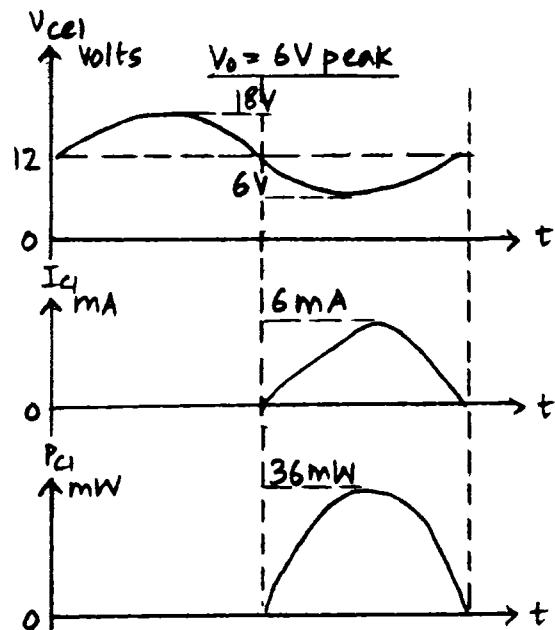
$$P_L = \frac{1}{2} \frac{\hat{V}_o^2}{R_L} = \frac{1}{2} \frac{11.8^2}{1} = 69.5 \text{ mW}$$

$$\eta_c = \frac{69.6}{90.2} = 77.2 \%$$

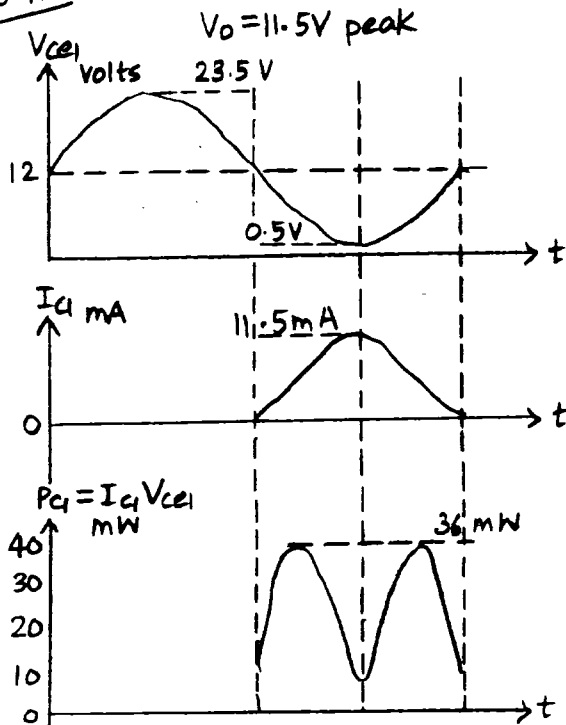
Max. device dissipation occurs

$$\text{When } I_c = \frac{V_{CC}}{2R_L} = 6 \text{ mA}$$

$$\therefore P_c = I_c V_{CE} = 6 \times 6 = 36 \text{ mW}$$



5.12

Peak P_C occurs for $V_{CE} = 6 \text{ V}$

5.13

$$\underline{V_o = 0}$$

$$I_{C1} = I_{C2} = I_{C3} = I_{C4} \approx 0.1 \text{ mA}$$

$$V_i = V_{BE2} = -V_T \ln \frac{10^{-4}}{10^{-15}} = -659 \text{ mV}$$

$$\underline{V_o = 5 \text{ V}}$$

$$I_{C1} \approx \frac{V_o}{R_L} = 5 \text{ mA}$$

$$V_{BE1} = 26 \ln \frac{5 \times 10^{-3}}{10^{-15}} = 760 \text{ mV}$$

$$I_{B1} = \frac{5}{150} = 0.033 \text{ mA}$$

$$\therefore I_{C3} = I_{C4} = 0.1 - 0.033 = 0.066 \text{ mA}$$

$$\therefore V_{BE3} = V_{BE4} = 26 \ln \frac{0.066 \times 10^{-3}}{10^{-15}} = 648 \text{ mV}$$

$$\therefore V_{BE2} = -(2 \times 648 - 760) = -536 \text{ mV}$$

$$\therefore I_{C2} = 10^{-15} e^{536/26} = 0.9 \text{ } \mu\text{A}$$

$$V_i = V_o + V_{BE2} = 5 - 0.536 = 4.46 \text{ V}$$

$$\underline{V_o = 10 \text{ V}}$$

$$I_{C1} \approx \frac{V_o}{R_L} = 10 \text{ mA}$$

$$V_{BE1} = 26 \ln \frac{10 \times 10^{-3}}{10^{-15}} = 778 \text{ mV}$$

$$I_{B1} = \frac{10}{150} = 0.066 \text{ mA}$$

$$\therefore I_{C3} = I_{C4} = 0.1 - 0.066 = 0.033 \text{ mA}$$

$$\therefore V_{BE3} = V_{BE4} = 26 \ln \frac{0.033 \times 10^{-3}}{10^{-15}} = 630 \text{ mV}$$

$$\therefore V_{BE2} = -(2 \times 630 - 778) = -481 \text{ mV}$$

$$\therefore I_{C2} = 10^{-15} e^{481/26} = 0.1 \text{ } \mu\text{A}$$

$$V_i = V_o + V_{BE2} = 10 - 0.48 = 9.52 \text{ V}$$

$$\underline{V_o = -5 \text{ V}}$$

$$I_{C2} \approx \frac{V_o}{R_L} \approx -5 \text{ mA}$$

$$\therefore V_{BE2} = -760 \text{ mV}$$

$$I_{C3} = I_{C4} \approx 0.1 \text{ mA}$$

$$\therefore V_{BE3} = V_{BE4} = 26 \ln \frac{10^{-4}}{10^{-15}} = 659 \text{ mV}$$

$$\therefore V_{BE1} = 2 \times 659 - 760 = 557 \text{ mV}$$

$$\therefore I_{C1} = 10^{-15} e^{557/26} = 2 \text{ } \mu\text{A}$$

$$V_i = V_o + V_{BE2} = -5 - 0.76 = -5.76 \text{ V}$$

$$\underline{V_o = -10 \text{ V}}$$

$$I_{C2} \approx -10 \text{ mA}$$

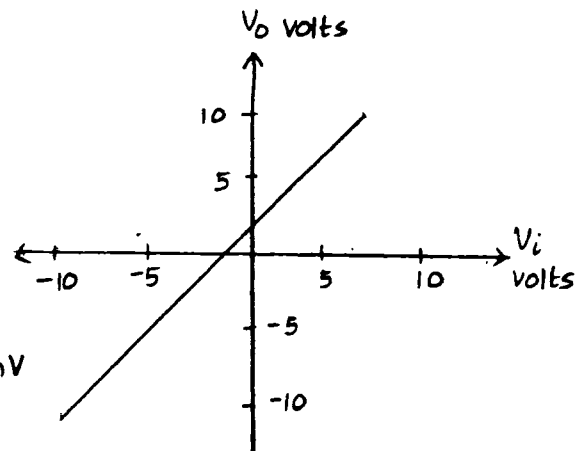
$$V_{BE2} = -778 \text{ mV}$$

$$V_{BE3} = V_{BE4} = 659 \text{ mV}$$

$$\therefore V_{BE1} = 2 \times 659 - 778 = 539 \text{ mV}$$

$$\therefore I_{C1} = 1 \text{ } \mu\text{A}$$

$$V_i = V_o + V_{BE2} = -10.78 \text{ V}$$



5.14

(a) $R_L = 10 \text{ k}\Omega$

$$V_o^- = -V_{CC} + V_{CE3(\text{sat})} + V_{be2}$$

$$= -15 + 0.2 + 0.7 = -14.1 \text{ V}$$

$$V_o^+ = \frac{V_{CC} - V_{be1}}{1 + \frac{R_1}{\beta_1 R_L}} = \frac{15 - 0.7}{1 + \frac{20}{50 \times 10}} = 13.8 \text{ V}$$

$R_L = 2 \text{ k}\Omega$

$V_o^- = -14.1 \text{ V}$

$$V_o^+ = \frac{15 - 0.7}{1 + \frac{20}{100}} = 11.9 \text{ V}$$

(b) $R_L = 10 \text{ k}\Omega$

$$P_L|_{\text{MAX}} = \frac{1}{2} \frac{\hat{V}_o^2}{R_L} = \frac{1}{2} \frac{13.8^2}{10} = 9.52 \text{ mW}$$

$$I_{\text{supply}} = \frac{1}{\pi} \frac{\hat{V}_o}{R_L} = \frac{1}{\pi} \frac{13.8}{10} = 0.44 \text{ mA}$$

$$P_{\text{supply}} = 2 \times 15 \times 0.44 = 13.2 \text{ mW}$$

$$\eta_c = \frac{9.52}{13.2} = 72.1\%$$

Average power dissipated per device

$$= \frac{1}{2} (P_{\text{supply}} - P_L)$$

$$= \frac{1}{2} (13.2 - 9.52) = 1.84 \text{ mW}$$

$R_L = 2 \text{ k}\Omega$

$$P_L|_{\text{MAX}} = \frac{1}{2} \frac{11.9^2}{2} = 35.4 \text{ mW}$$

$$I_{\text{supply}} = \frac{1}{\pi} \frac{11.9}{2} = 1.89 \text{ mA}$$

$$P_{\text{supply}} = 2 \times 15 \times 1.89 = 56.8 \text{ mW}$$

$$\eta_c = \frac{35.4}{56.8} = 62.3\%$$

Average power dissipated per device

$$= \frac{1}{2} \times (56.8 - 35.4) = 10.7 \text{ mW}$$

5.15

(a) $R_L = 10 \text{ k}\Omega$

$$V_o^- = -V_{CC} + V_{CE17(\text{sat})} + V_{be23} + V_{be20}$$

$$= -15 + 0.2 + 0.7 + 0.7 = -13.4 \text{ V}$$

$$V_o^+ = V_{CC} - V_{CE13A(\text{sat})} - V_{be14}$$

$$= 15 - 0.2 - 0.7 = 14.1 \text{ V}$$

$R_L = 1 \text{ k}\Omega$

$V_o^- = -13.4 \text{ V}$

$V_o^+ = 14.1 \text{ V}$

$R_L = 200 \Omega$

$V_o^- = -13.4 \text{ V}$

For positive outputs, Q_{14} is limited to a current

$$I_o|_{\text{MAX}} = \beta_{14} \times 0.22 = 200 \times 0.22 = 44 \text{ mA}$$

$$\therefore V_o^+ = 44 \times 0.2 = 8.8 \text{ V}$$

(b) $R_L = 1 \text{ k}\Omega$

$$P_L|_{\text{MAX}} = \frac{1}{2} \frac{\hat{V}_o^2}{R_L} = \frac{1}{2} \frac{13.4^2}{1} = 89.8 \text{ mW}$$

$$I_{\text{supply}} = \frac{1}{\pi} \frac{\hat{V}_o}{R_L} = \frac{1}{\pi} \frac{13.4}{1} = 4.27 \text{ mA}$$

$$P_{\text{supply}} = 2 \times V_{CC} \times I_{\text{supply}}$$

$$= 30 \times 4.27 = 128 \text{ mW}$$

$$\therefore \eta_c = \frac{89.8}{128} = 70\%$$

Peak dissipation occurs for

$$V_o = V_{ce} = \frac{V_{CC}}{2} = 7.5 \text{ V}$$

$$I_c = \frac{V_o}{R_L} = 7.5 \text{ mA}$$

$$\therefore P_c = 7.5 \times 7.5 = 56.3 \text{ mW}$$

5.16

(a) Peak device dissipation = $\frac{V_{CC}^2}{4R_L}$

Put $\frac{V_{CC}^2}{4R_L} = 100 \times 10^{-3}$

$\therefore R_L = \frac{15^2}{400 \times 10^{-3}} = 563 \Omega$

MAX. $P_L = \frac{1}{2} \frac{\hat{V}_o^2}{R_L} = \frac{1}{2} \frac{13.4^2}{0.563} = 160 \text{ mW}$

$I_{\text{supply}} = \frac{1}{\pi} \frac{\hat{V}_o}{R_L} = \frac{1}{\pi} \frac{13.4}{0.563} = 7.58 \text{ mA}$

$P_{\text{supply}} = 30 \times 7.58 = 227 \text{ mW}$

$\eta_c = \frac{160}{227} = 70.4\%$

(b) $\frac{V_{CC}^2}{4R_L} = 200 \times 10^{-3}$

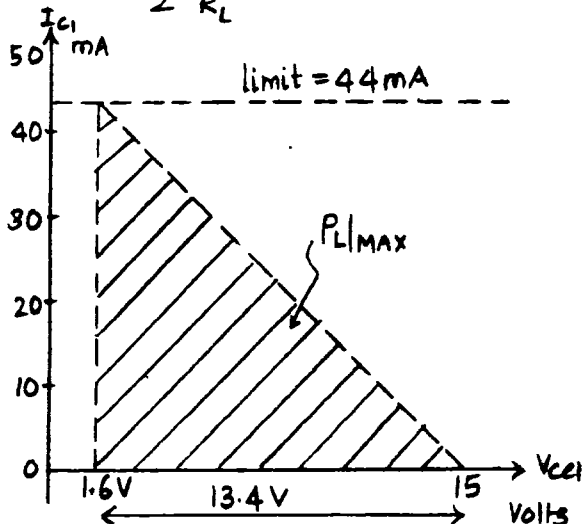
$\therefore R_L = 282 \Omega$

However for this value of R_L , the output current is limited

$I_{O|_{\text{max}}} = \beta_{14} \times 0.22 = 44 \text{ mA}$

$\therefore V_o^+ = 0.282 \times 44 = 12.4 \text{ V} = \hat{V}_o$

$\therefore P_L = \frac{1}{2} \frac{\hat{V}_o^2}{R_L} = 273 \text{ mW}$



Max. P_L occurs as shown above

Where $R_L = \frac{13.4}{44} = 304 \Omega$

(note: Max. device dissipation is less than 200 mW)

$\therefore P_L = \frac{1}{2} \frac{\hat{V}_o^2}{R_L} = \frac{1}{2} \frac{13.4^2}{304} = 295 \text{ mW}$

$I_{\text{supply}} = \frac{1}{\pi} \frac{\hat{V}_o}{R_L} = 14.0 \text{ mA}$

$P_{\text{supply}} = 14.0 \times 30 = 420 \text{ mW}$

$\eta_c = \frac{295}{420} = 70\%$

5.17

$$V_o = -10V, R_L = 1k\Omega$$

$$\therefore I_{C20} \approx -\frac{10}{1} = -10 \text{ mA}$$

$$V_{BE20} = -V_T \ln \frac{10^{-2}}{10^{-4}} = -718 \text{ mV}$$

$$I_{C19} = I_{C18} = 0.22 \text{ mA}$$

$$\therefore V_{BE19} = V_{BE18} = 619 \text{ mV}$$

$$\therefore V_{BE14} = 2 \times 619 - 718 = 520 \text{ mV}$$

$$\therefore I_{C14} = 10^{-14} e^{520/26} = 4.9 \mu\text{A}$$

$$I_{C23} = 0.22 \text{ mA} + I_{B20} = 0.42 \text{ mA}$$

5.18

$$(a) V_o^+ = V_{CC} - V_{CE3(sat)} - V_{be5} - V_{be4}$$

$$= 12 - 0.2 - 0.7 - 0.7 = 10.4 \text{ V}$$

$$V_o^- = -V_{CC} + V_{CE2(sat)} + V_{be1} + V_{D1}$$

$$= -12 + 0.2 + 0.7 + 0.7 = 10.4 \text{ V}$$

(b) For $V_o = 0$, D_1 , Q_4 and Q_5 are off

$$P_Q = 2 \times 12 \times 2 \text{ mW} = 48 \text{ mW}$$

$$(c) P_L|_{\max} = \frac{1}{2} \frac{10.4^2}{8} = 6.76 \text{ W}$$

$$I_{\text{supply}} = \frac{1}{\pi} \frac{\hat{V}_o}{R_L} = \frac{1}{\pi} \frac{10.4}{8} = 414 \text{ mA}$$

$$\therefore P_{\text{supply}} = 2 \times 12 \times 414 \times 10^{-3} = 9.94 \text{ W}$$

$$P_{\text{supply}} + P_Q = 9.99 \text{ W}$$

$$\therefore \eta = \frac{6.76}{9.99} = 67.7\%$$

$$P_E|_{\max} = \frac{1}{4} \frac{V_{CC}^2}{R_L} = \frac{1}{4} \frac{12^2}{8} = 4.5 \text{ W}$$

ALL-NPN DARLINGTON OUTPUT STAGE

VCC	100	0	12	
VBE	200	0	-12	
Q1	5	7	200	NPN
Q2	5	6	7	NPN_SMALL
Q3	3	10	100	PNP
Q4	100	3	9	NPN_SMALL
Q5	100	9	8	NPN
QD1	8	8	5	NPN
QD2	4	4	5	NPN_SMALL
QD3	3	3	4	NPN_SMALL
RL	8	0	8	

* IN FIG. 5.42, VBIAS COULD BE ADJUSTED BY TRIAL AND ERROR

* TO SET THE COLLECTOR CURRENT OF Q3 EQUAL TO 2 MA,

* BUT THIS PROCESS MAY REQUIRE MANY ITERATIONS.

* SO INSTEAD, Q6 AND IBIAS ARE ADDED TO FORM A

* CURRENT MIRROR TO SET UP THE DC COLLECTOR CURRENT IN Q3.

* HERE ONLY TWO ITERATIONS ARE REQUIRED

* BECAUSE CURRENT MIRRORS ARE LINEAR.

Q6 10 10 100 PNP

IBIAS 10 200 1.523M

.MODEL NPN NPN RB=1 BF=100 IS=1E-15 RC=0.2 VAF=30

.MODEL NPN_SMALL NPN RB=100 BF=100 IS=1E-17 RC=20 VAF=30

.MODEL PNP PNP RB=100 BF=100 IS=1E-16 RC=50 VAF=30

* THE DC INPUT VOLTAGE IS ADJUSTED BY TRIAL AND ERROR

* TO SET THE DC OUTPUT VOLTAGE TO ZERO.

VIN 6 200 1.45

.OPTIONS NOPAGE NOMOD

.WIDTH OUT=80

.OP

.DC VIN 1 2.5 0.05

.PLOT DC V(8)

.END

***** DC TRANSFER CURVES THOM= 27.000 TEMP= 27.000

VOLT	V(8)					
(A)		-2.000E+01	-1.000E+01	0.	1.000E+01	2.000E+01
		+	+	+	+	+
1.000E+00	1.01E+01	+	+	+	A	+
1.050E+00	1.01E+01	+	+	+	+	+
1.100E+00	1.01E+01	+	+	+	A	+
1.150E+00	1.01E+01	+	+	+	+	+
1.200E+00	1.01E+01	+	+	+	+	+
1.250E+00	1.01E+01	+	+	+	A	+
1.300E+00	1.01E+01	+	+	+	+	+
1.350E+00	1.01E+01	+	+	+	A	+
1.400E+00	9.97E+00	+	+	+	+	+
1.450E+00	-2.80E-03	+	+	+	A	+
1.500E+00	-3.31E-02	+	+	+	A	+
1.550E+00	-1.12E-01	+	+	+	+	+
1.600E+00	-3.15E-01	+	+	+	+	+
1.650E+00	-8.23E-01	+	+	+	A+	+
1.700E+00	-1.99E+00	+	+	+	A	+
1.750E+00	-4.34E+00	+	+	+	A	+
1.800E+00	-8.00E+00	+	+	+	+	+
1.850E+00	-9.84E+00	+	A	+	+	+
1.900E+00	-9.87E+00	+	A	+	+	+
1.950E+00	-9.89E+00	+	A	+	+	+
2.000E+00	-9.91E+00	+	A	+	+	+
2.050E+00	-9.92E+00	+	A	+	+	+
2.100E+00	-9.94E+00	+	A	+	+	+
2.150E+00	-9.95E+00	+	A	+	+	+
2.200E+00	-9.96E+00	+	A	+	+	+
2.250E+00	-9.97E+00	+	A	+	+	+
2.300E+00	-9.99E+00	+	A	+	+	+
2.350E+00	-1.00E+01	+	A	+	+	+
2.400E+00	-1.00E+01	+	A	+	+	+
2.450E+00	-1.00E+01	+	A	+	+	+
2.500E+00	-1.00E+01	+	A	+	+	+


```

**** OPERATING POINT INFORMATION      TNOm= 27.000 TEMP= 27.000
NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:3      = 1.016E+00 0:4      = 1.634E-01 0:5      = -6.900E-01
+0:6      = -1.055E+01 0:7      = -1.127E+01 0:8      = -2.796E-03
+0:9      = 5.112E-01 0:10     = 1.121E+01 0:100     = 1.200E+01
+0:200    = -1.200E+01

```

**** BIPOLAR JUNCTION TRANSISTORS

```

SUBCKT
ELEMENT 0:Q1      0:Q2      0:Q3      0:Q4      0:Q5
MODEL   0:NPN      0:NPN_SGAL 0:PMP      0:NPN_SGAL 0:NPN
IB       1.725E-05 1.289E-07 -1.497E-05 3.096E-11 4.272E-09
IC       2.333E-03 1.712E-05 -2.001E-03 4.230E-09 5.908E-07
VBE      7.288E-01 7.212E-01 -7.861E-01 5.057E-01 5.140E-01
VCE      1.131E+01 1.058E+01 -1.098E+01 1.148E+01 1.200E+01
VBC      -1.058E+01 -9.860E+00 1.019E+01 -1.098E+01 -1.148E+01
VS       6.905E-01 6.904E-01 -1.121E+01 -1.200E+01 -1.200E+01
POWER    2.640E-02 1.813E-04 2.198E-02 4.861E-08 7.093E-06
BETAD    1.352E+02 1.328E+02 1.336E+02 1.366E+02 1.383E+02
GM       9.016E-02 6.616E-04 7.730E-02 1.634E-07 2.283E-05
RPI      1.499E+03 2.007E+05 1.728E+03 8.354E+08 6.054E+06
RX       1.000E+00 1.000E+02 1.000E+02 1.000E+02 1.000E+00
RO       1.739E+04 2.328E+06 2.004E+04 9.689E+09 7.022E+07
BETAAC   1.351E+02 1.327E+02 1.335E+02 1.365E+02 1.382E+02

```

```

SUBCKT
ELEMENT 0:QD1     0:QD2     0:QD3     0:Q6
MODEL   0:NPN      0:NPN_SGAL 0:NPN_SGAL 0:PMP
IB       3.466E-06 1.983E-05 1.983E-05 -1.497E-05
IC       3.466E-04 1.981E-03 1.981E-03 -1.493E-03
VBE      6.873E-01 8.535E-01 8.535E-01 -7.861E-01
VCE      6.873E-01 8.535E-01 8.535E-01 -7.861E-01
VBC      0.         0.         0.         0.
VS       2.865E-03 -1.238E-01 -9.772E-01 -1.121E+01
POWER    2.406E-04 1.707E-03 1.707E-03 1.186E-03
BETAD    9.999E+01 9.987E+01 9.987E+01 9.975E+01
GM       1.339E-02 7.651E-02 7.651E-02 5.768E-02
RPI      7.462E+03 1.304E+03 1.304E+03 1.728E+03
RX       1.000E+00 1.000E+02 1.000E+02 1.000E+02
RO       8.655E+04 1.512E+04 1.512E+04 2.004E+04
BETAAC   9.991E+01 9.978E+01 9.978E+01 9.967E+01

```

5.19

$$(a) V_o^+ = V_{CC} - V_{BE2} - V_{CE7(sat)}$$

$$= 15 - 0.7 - 0.2 = 14.1 \text{ V}$$

$$V_o^- = -V_{CC} + V_{CE1(sat)} + V_{BE3}$$

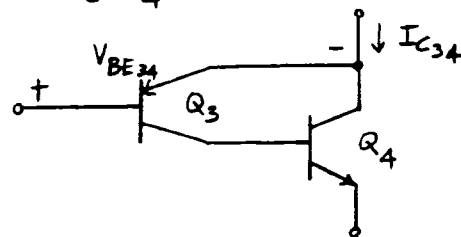
$$= -15 + 0.2 + 0.7 = -14.1 \text{ V}$$

$$(b) I_{C7} = 0.15 \text{ mA}$$

$$\therefore I_{C5} = I_{C6} \approx 0.15 \text{ mA}$$

$$\therefore V_{BE5} = V_{BE6} = V_T \ln \frac{0.15 \times 10^{-3}}{10^{-14}} = 609 \text{ mV}$$

$$I_{C1} \approx 0.15 \text{ mA}$$

For Q_3 - Q_4 

$$I_{C34} = (\beta_4 + 1) I_{S3} e^{-V_{BE34}/V_T}$$

$$2 V_{BE6} = V_{BE2} - V_{BE34}$$

$$= V_T \ln \frac{I_{C2}}{I_{S2}} + V_T \ln \frac{I_{C34}}{(\beta_4 + 1) I_{S3}}$$

$$\text{But } I_{C34} = I_{C2}, \text{ because } V_o = 0$$

$$\therefore 1218 \text{ mV} = 26 \ln \frac{I_{C2}^2}{I_{S2} (\beta_4 + 1) I_{S3}}$$

$$\therefore \frac{1218}{26} = \ln \frac{I_{C2}^2}{10^{-14} \times 151 \times 10^{-15}}$$

$$\therefore I_{C2} = 0.58 \text{ mA}$$

$$(c) P_{C|_{\max}} = \frac{V_{CC}^2}{4R_L} = 100 \times 10^{-3} \text{ W}$$

$$\therefore R_L = \frac{225}{0.4} = 563 \Omega$$

This requires $I_{C2(\text{peak})} = \frac{14.1}{563} = 25 \text{ mA}$

But $\beta_2 \times 0.15 = 150 \times 0.15 = 22.5 \text{ mA}$

$\therefore Q_2$ cannot supply this current
max. power occurs when

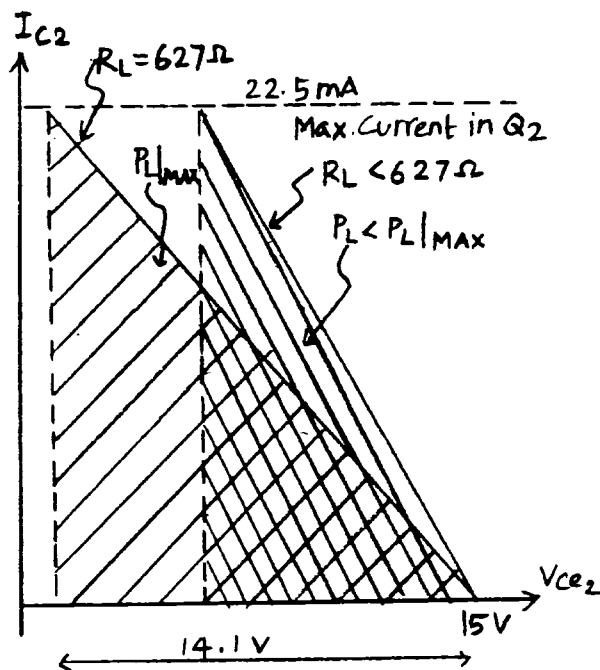
$$\frac{14.1}{R_L} = 22.5 \text{ mA}$$

$\therefore R_L = 627 \Omega$ — then $P_{C|_{\text{max}}} < 100 \text{ mW}$

$$\therefore P_L = \frac{1}{2} \frac{\hat{V}_o^2}{R_L} = \frac{1}{2} \frac{14.1^2}{627} = 159 \text{ mW}$$

Peak current in $Q_4 = 22.5 \text{ mA}$

Peak current in $Q_3 = \frac{22.5}{150} = 0.15 \text{ mA}$



5.20

(a) Bias $V_0 = 0$

$$|I_{C5}| = 100 \mu A$$

$$|I_{C6}| = 500 \mu A$$

$$|I_{D3}| = |I_{B5}| + |I_{B6}|$$

$$= \frac{600 \mu A}{20} = 30 \mu A$$

$$|I_{D1}| = \frac{V_{BE3}}{R_1} = \frac{0.8}{10K} = 80 \mu A$$

$$I_{C3} = 500 - 80 = 420 \mu A$$

$$|I_{D2}| = \frac{V_{BE2}}{R_2} = \frac{0.8}{10K} = 80 \mu A$$

From KVL,

$$V_{GS1} + V_{BE1} = V_{GS2} + V_{BE3}$$

(where $V_{GS1} < 0$ and $V_{GS2} < 0$)Since $I_{D1} = I_{D2}$, $V_{GS1} = V_{GS2}$ Then $V_{BE1} = V_{BE3}$ as expectedThen $I_{C1} = I_{C3} = 420 \mu A$ and $I_{C2} = I_{C1} - |I_{D2}| = 340 \mu A$ and V_{BE2}

(b) Maximum swing

$$V_0^+ = 5 - V_{BE1} - V_{CE6}(\text{sat}) - |I_{C6} R_4|$$

$$= 5 - 0.8 - 0.1 - 500 \mu A (100)$$

$$= 4.05 V$$

Minimum swing

If $V_i = -5V$, Q_1 is off

$$V_0^- = V_i + V_{SG2} = V_i + |V_{GS2}|$$

$$V_0^- = V_i + |V_{t2}| + |V_{GS2} - V_{t2}|$$

If M_2 operates in the active region,

$$|V_{GS2} - V_{t2}| = \sqrt{\frac{2|I_{D2}|}{K'(W/L)_2}}$$

$$= \sqrt{\frac{2(80)}{26(500)}} = 0.11 V$$

$$\text{and } V_0^- = -5 + 0.7 + 0.11 = -4.19 V$$

$$\text{But then } V_{SD2} = V_0 - (-5 + V_{BE2})$$

$$= V_0 - (-5 + 0.8)$$

$$= V_0 + 4.2$$

$$= -4.19 + 4.2 = 0.01 V$$

Since $V_{SD2} < |V_{GS2} - V_{t2}|$, M_2 operates in the triode region

A quadratic equation could be solved to find V_{SD2} , but it is not worth the trouble because V_0^- is set mainly by the supply voltage and V_{BE2}

For simplicity, assume $V_{SD2} = 0.1 V$

$$\text{Then } V_0^- = -5 + V_{BE2} + V_{SD2}$$

$$= -5 + 0.8 + 0.1$$

$$= -4.1 V$$


```

**** OPERATING POINT INFORMATION      TNOM= 27.000 TEMP= 27.000
      NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:3      = 4.947E+00 0:4      = 4.160E+00 0:5      = 4.946E+00
+0:6      = 2.206E+00 0:7      = 7.179E-01 0:8      = -6.835E-02
+0:9      = -8.093E-01 0:10     = -2.920E-02 0:11     = -4.249E+00
+0:21     = 5.000E+00 0:100     = 5.000E+00 0:110     = -2.920E-02
+0:113     = -4.249E+00 0:200     = -5.000E+00

```

**** BIPOLAR JUNCTION TRANSISTORS

```

SUBCKT
ELEMENT 0:Q1      0:Q2      0:Q3      0:Q5      0:Q6
MODEL   0:NPN     0:NPN     0:NPN     0:PNP     0:PNP
IB      6.547E-06  7.341E-06  5.166E-06 -4.694E-06 -2.280E-05
IC      5.879E-04  6.581E-04  4.226E-04 -1.000E-04 -5.084E-04
VBE     7.471E-01  7.501E-01  7.410E-01 -7.867E-01 -7.860E-01
VCE     5.029E+00  4.970E+00  1.527E+00 -2.741E+00 -4.229E+00
VBC     -4.282E+00 -4.220E+00 -7.862E-01  1.954E+00  3.443E+00
VS      -5.000E+00  2.920E-02 -7.179E-01 -4.161E+00 -4.161E+00
POWER   2.961E-03  3.277E-03  6.492E-04  2.778E-04  2.168E-03
BTAD    8.978E+01  8.964E+01  8.179E+01  2.130E+01  2.229E+01
GM      2.271E-02  2.543E-02  1.633E-02  3.863E-03  1.964E-02
RPI     3.950E+03  3.523E+03  5.006E+03  5.510E+03  1.134E+03
RX      1.600E+01  1.600E+01  1.600E+01  2.000E+02  4.000E+01
RO      6.682E+04  5.959E+04  8.468E+04  3.195E+05  6.578E+04
BTAA    8.972E+01  8.958E+01  8.173E+01  2.128E+01  2.227E+01

```

**** MOSFETS

```

SUBCKT
ELEMENT 0:M1      0:M2      0:M3
MODEL   0:PMOS1   0:PMOS1   0:PMOS2
ID      -7.926E-05 -8.235E-05 -2.750E-05
IBS     0.         0.         0.
IBD     7.862E-15  4.221E-14  4.161E-14
VGS     -7.862E-01 -7.801E-01 -1.954E+00
VDS     -7.862E-01 -4.220E+00 -4.160E+00
VBS     0.         0.         0.
VTH     -7.000E-01 -7.000E-01 -7.000E-01
VDSAT   -8.625E-02 -8.010E-02 -1.254E+00
BETA     2.131E-02  2.567E-02  3.493E-05
GAM EFF  0.         0.         0.
GM      1.838E-03  2.056E-03  4.383E-05
GDS     4.722E-06  4.072E-06  6.091E-07
GMB     0.         0.         0.

```

***** TRANSIENT ANALYSIS TNOM= 27.000 TEMP= 27.000

```

      TIME      I(VIC1)
(A)      -5.000E-03  0.      5.000E-03  1.000E-02  1.500E-02
      +      +      +      +      +
0.      5.88E-04 -----A-----
4.000E-06  2.26E-03 +      +      A+      +      +      +      +
8.000E-06  4.53E-03 +      +      +      A+      +      +      +
1.200E-05  6.55E-03 +      +      +      +      A      +      +
1.600E-05  8.14E-03 +      +      +      +      +      A      +
2.000E-05  9.21E-03 +      +      +      +      +      +      A      +
2.400E-05  9.68E-03 +      +      +      +      +      +      +      A+
2.800E-05  9.52E-03 +      +      +      +      +      +      +      +      A+
3.200E-05  8.74E-03 +      +      +      +      +      +      A      +
3.600E-05  7.40E-03 +      +      +      +      A      +      +
4.000E-05  5.57E-03 -----A-----
4.400E-05  3.41E-03 +      +      +      A      +      +      +
4.800E-05  1.13E-03 +      +      A      +      +      +      +
5.200E-05  4.45E-04 +      +      A      +      +      +      +
5.600E-05  2.74E-04 +      +      A      +      +      +      +
6.000E-05  1.81E-04 +      +      A      +      +      +      +
6.400E-05  1.29E-04 +      A      +      +      +      +      +
6.800E-05  1.02E-04 +      A      +      +      +      +      +
7.200E-05  8.84E-05 +      A      +      +      +      +      +
7.600E-05  8.57E-05 +      A      +      +      +      +      +
8.000E-05  9.35E-05 -----A-----
8.400E-05  1.13E-04 +      A      +      +      +      +      +
8.800E-05  1.52E-04 +      A      +      +      +      +      +
9.200E-05  2.22E-04 +      A      +      +      +      +      +
9.600E-05  3.49E-04 +      A      +      +      +      +      +
1.000E-04  5.88E-04 +      A      +      +      +      +      +
      +      +      +      +      +

```

***** TRANSIENT ANALYSIS TNOM= 27.000 TEMP= 27.000

```

      TIME      I(VIC2)
(A)      0.      5.000E-03  1.000E-02  1.500E-02  2.000E-02
      +      +      +      +      +
0.      6.58E-04 -----A-----
4.000E-06  7.94E-12 A      +      +      +      +      +      +
8.000E-06  5.85E-12 A      +      +      +      +      +      +
1.200E-05  6.31E-12 A      +      +      +      +      +      +
1.600E-05  6.65E-12 A      +      +      +      +      +      +
2.000E-05  6.86E-12 A      +      +      +      +      +      +
2.400E-05  6.96E-12 A      +      +      +      +      +      +
2.800E-05  6.93E-12 A      +      +      +      +      +      +
3.200E-05  6.77E-12 A      +      +      +      +      +      +
3.600E-05  6.49E-12 A      +      +      +      +      +      +
4.000E-05  6.09E-12 A -----A-----
4.400E-05  5.60E-12 A      +      +      +      +      +      +
4.800E-05  7.19E-06 A      +      +      +      +      +      +
5.200E-05  1.76E-03 +      A      +      +      +      +      +
5.600E-05  4.02E-03 +      A      +      +      +      +      +
6.000E-05  6.13E-03 +      +      A      +      +      +      +
6.400E-05  7.91E-03 +      +      +      A      +      +      +
6.800E-05  9.22E-03 +      +      +      +      A      +      +
7.200E-05  9.98E-03 +      +      +      +      +      A      +
7.600E-05  1.01E-02 +      +      +      +      +      +      A      +
8.000E-05  9.67E-03 -----A-----
8.400E-05  8.62E-03 +      +      +      A      +      +      +
8.800E-05  7.06E-03 +      +      A+      +      +      +      +
9.200E-05  5.10E-03 +      A      +      +      +      +      +
9.600E-05  2.90E-03 +      A      +      +      +      +      +
1.000E-04  6.58E-04 +      A      +      +      +      +      +
      +      +      +      +      +

```

***** TRANSIENT ANALYSIS TNOM= 27.000 TEMP= 27.000

```

      TIME      I(VID2)
(A)      0.      1.000E-04  2.000E-04  3.000E-04  4.000E-04
      +      +      +      +      +
0.      8.23E-05 -----A-----
4.000E-06  2.50E-05 +      A      +      +      +      +      +
8.000E-06  6.79E-06 +      A      +      +      +      +      +
1.200E-05  1.36E-06 A      +      +      +      +      +      +
1.600E-05  5.51E-08 A      +      +      +      +      +      +
2.000E-05  1.38E-11 A      +      +      +      +      +      +
2.400E-05  1.40E-11 A      +      +      +      +      +      +
2.800E-05  1.39E-11 A      +      +      +      +      +      +
3.200E-05  1.36E-11 A      +      +      +      +      +      +
3.600E-05  4.26E-07 A      +      +      +      +      +      +
4.000E-05  3.41E-06 A -----A-----
4.400E-05  1.35E-05 +      A      +      +      +      +      +
4.800E-05  5.55E-05 +      A      +      +      +      +      +
5.200E-05  9.74E-05 +      A      +      +      +      +      +
5.600E-05  1.26E-04 +      +      A      +      +      +      +
6.000E-05  1.52E-04 +      +      +      A      +      +      +
6.400E-05  1.74E-04 +      +      +      +      A      +      +
6.800E-05  1.90E-04 +      +      +      +      +      A+      +
7.200E-05  2.00E-04 +      +      +      +      +      +      A      +
7.600E-05  2.02E-04 +      +      +      +      A      +      +
8.000E-05  1.96E-04 -----A-----
8.400E-05  1.83E-04 +      +      +      A      +      +      +
8.800E-05  1.63E-04 +      +      +      A      +      +      +
9.200E-05  1.39E-04 +      +      A+      +      +      +      +
9.600E-05  1.12E-04 +      +      A      +      +      +      +
1.000E-04  8.23E-05 +      A+      +      +      +      +      +
      +      +      +      +

```

***** TRANSIENT ANALYSIS THOM= 27.000 TEMP= 27.000

TIME	V(10)					
(A)	-4.000E+00	-2.000E+00	0.	2.000E+00	4.000E+00	
0.	-2.92E-02					
4.000E-06	4.51E-01	+	+	+	+	+
8.000E-06	9.15E-01	+	+	+	+	+
1.200E-05	1.32E+00	+	+	+	+	+
1.600E-05	1.64E+00	+	+	+	+	+
2.000E-05	1.86E+00	+	+	+	+	+
2.400E-05	1.95E+00	+	+	+	+	+
2.800E-05	1.92E+00	+	+	+	+	+
3.200E-05	1.76E+00	+	+	+	+	+
3.600E-05	1.49E+00	+	+	+	+	+
4.000E-05	1.12E+00	+	+	+	+	+
4.400E-05	6.86E-01	+	+	+	+	+
4.800E-05	2.15E-01	+	+	+	+	+
5.200E-05	-2.82E-01	+	+	+	+	+
5.600E-05	-7.74E-01	+	+	+	+	+
6.000E-05	-1.22E+00	+	+	+	+	+
6.400E-05	-1.59E+00	+	+	+	+	+
6.800E-05	-1.86E+00	+	+	+	+	+
7.200E-05	-2.01E+00	+	+	+	+	+
7.600E-05	-2.05E+00	+	+	+	+	+
8.000E-05	-1.95E+00	+	+	+	+	+
8.400E-05	-1.73E+00	+	+	+	+	+
8.800E-05	-1.41E+00	+	+	+	+	+
9.200E-05	-1.00E+00	+	+	+	+	+
9.600E-05	-5.31E-01	+	+	+	+	+
1.000E-04	-2.92E-02	+	+	+	+	+

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(10)

DC COMPONENT = -4.333D-02

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	2.004E+00	1.000E+00	4.267E-04	0.
2	2.000E+04	4.438E-03	2.215E-03	9.067E+01	9.067E+01
3	3.000E+04	6.157E-03	3.072E-03	-1.799E+02	-1.799E+02
4	4.000E+04	3.486E-03	1.740E-03	8.912E+01	8.912E+01
5	5.000E+04	1.974E-03	9.851E-04	1.794E+02	1.794E+02
6	6.000E+04	2.250E-03	1.123E-03	9.093E+01	9.093E+01
7	7.000E+04	6.148E-04	3.068E-04	1.744E+02	1.744E+02
8	8.000E+04	1.536E-03	7.664E-04	9.086E+01	9.086E+01
9	9.000E+04	4.136E-04	2.064E-04	-1.251E+01	-1.251E+01

TOTAL HARMONIC DISTORTION = 4.508E-01 PERCENT

BICMOS CLASS-AB OUTPUT STAGE (PEAK OUTPUT AMPLITUDE = 4 V)

* BIPOLAR PARAMETERS FROM FIG. 2.32 AND

* PMOS PARAMETERS FROM TABLE 2.3

VCC	100	0	5		
VBE	200	0	-5		
Q1	21	7	10	NPN	25
Q2	110	13	200	NPN	25
Q3	7	8	9	NPN	25
Q5	6	4	3	PNP	
Q6	7	4	5	PNP	5
M1	8	8	7	PMOS1	W=500U L=1U
M2	113	9	10	PMOS1	W=500U L=1U
M3	0	6	4	PMOS2	W=2U L=2U
R1	8	9	10K		
R2	13	200	10K		
R3	100	3	500		
R4	100	5	100		
RL	10	0	200		
IBIAS	6	0	100U		

* ZERO-VOLTAGE VOLTAGE SOURCES TO MEASURE TRANSISTOR CURRENTS

VIC1	100	21	0
VID2	113	13	0
VIC2	10	110	0

.MODEL NPN NPN RB=400 BF=80 IS=6E-18 VAF=35
.MODEL PNP PNP RB=200 BF=20 IS=6E-18 VAF=30
.MODEL PMOS1 PMOS KP=26U VTO=-0.7 LAMBDA=0.0625 LD=0.18U
.MODEL PMOS2 PMOS KP=26U VTO=-0.7 LAMBDA=0.0244 LD=0.18U
*LAMBDA1 = (DXD/DVDS)/LEFF = 0.04/(1-2*0.18) = 0.0625 V*{-1}
*LAMBDA2 = (DXD/DVDS)/LEFF = 0.04/(2-2*0.18) = 0.0244 V*{-1}

* THE DC INPUT VOLTAGE IS ADJUSTED BY TRIAL AND ERROR

* TO SET THE DC OUTPUT VOLTAGE TO ZERO.

* THE PEAK INPUT AMPLITUDE IS SET BY TRIAL AND ERROR

* SO THAT THE PEAK OUTPUT AMPLITUDE IS 4 V.

VI 9 0 SIN -0.8093 4.14 10K 0 0

.OPTIONS NOPAGE NOMOD

.WIDTH OUT=80

.OP

.DC VI -5 5 0.5

.PLOT DC V(10)

.TRAN 4U 100U

.PLOT TRAN I(VIC1)

.PLOT TRAN I(VIC2)

.PLOT TRAN I(VID2)

.PLOT TRAN V(10)

.FOUR 10K V(10)

.END

**** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:3	= 4.947E+00 0:4	= 4.160E+00 0:5	= 4.946E+00		
+0:6	= 2.206E+00 0:7	= 7.179E-01 0:8	= -6.835E-02		
+0:9	= -8.093E-01 0:10	= -2.920E-02 0:13	= -4.249E+00		
+0:21	= 5.000E+00 0:100	= 5.000E+00 0:110	= -2.920E-02		
+0:113	= -4.249E+00 0:200	= -5.000E+00			

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT

ELEMENT	0:Q1	0:Q2	0:Q3	0:Q5	0:Q6
MODEL	0:NPN	0:NPN	0:NPN	0:PNP	0:PNP
IB	6.547E-06	7.341E-06	5.166E-06	-4.694E-06	-2.280E-05
IC	5.879E-04	6.581E-04	4.226E-04	-1.000E-04	-5.084E-04
VBE	7.471E-01	7.501E-01	7.410E-01	-7.867E-01	-7.860E-01
VCE	5.029E+00	4.970E+00	1.527E+00	-2.741E+00	-4.229E+00
VBC	-4.282E+00	-4.220E+00	-7.862E-01	1.954E+00	3.443E+00
VS	-5.000E+00	2.920E-02	-7.179E-01	-4.161E+00	-4.161E+00
POWER	2.961E-03	3.277E-03	6.492E-04	2.778E-04	2.168E-03
BETAD	8.978E+01	8.964E+01	8.179E+01	2.130E+01	2.229E+01
GM	2.271E-02	2.543E-02	1.633E-02	3.863E-03	1.964E-02
RPI	3.950E+03	3.523E+03	5.006E+03	5.510E+03	1.134E+03
RX	1.600E+01	1.600E+01	1.600E+01	2.000E+02	4.000E+01
RO	6.682E+04	5.959E+04	8.468E+04	3.195E+05	6.578E+04
BETAAC	8.972E+01	8.958E+01	8.173E+01	2.128E+01	2.227E+01

**** MOSFETS

SUBCKT

```

ELEMENT 0:M1 0:M2 0:M3
MODEL 0:PMOS1 0:PMOS1 0:PMOS2
ID -7.926E-05 -8.235E-05 -2.750E-05
IBS 0. 0. 0.
IBD 7.862E-15 4.221E-14 4.161E-14
VGS -7.862E-01 -7.801E-01 -1.954E+00
VDS -7.862E-01 -4.220E+00 -4.160E+00
VBS 0. 0. 0.
VTH -7.000E-01 -7.000E-01 -7.000E-01
VDSAT -8.625E-02 -8.010E-02 -1.254E+00
BETA 2.131E-02 2.567E-02 3.493E-05
GAM EFF 0. 0. 0.
GM 1.838E-03 2.056E-03 4.383E-05
GDS 4.722E-06 4.072E-06 6.091E-07
GMB 0. 0. 0.

```

***** TRANSIENT ANALYSIS THOM= 27.000 TEMP= 27.000

```

TIME I(VIC1)
(A ) 0. 5.000E-03 1.000E-02 1.500E-02 2.000E-02
0. 5.88E-04 +A-----+-----+-----+-----+
4.000E-06 4.66E-03 + + A+ + + + + + + +
8.000E-06 9.29E-03 + + + + A+ + + + + + +
1.200E-05 1.33E-02 + + + + + A+ + + + + +
1.600E-05 1.66E-02 + + + + + + A+ + + + +
2.000E-05 1.87E-02 + + + + + + + A+ + + +
2.400E-05 1.96E-02 + + + + + + + + A+ + +
2.800E-05 1.93E-02 + + + + + + + + + A+ +
3.200E-05 1.78E-02 + + + + + + + + + +A+ +
3.600E-05 1.51E-02 + + + + + + + A+ + + +
4.000E-05 1.14E-02 +-----+-----+-----+-----+
4.400E-05 7.02E-03 + + A+ + + + + + + +
4.800E-05 2.27E-03 + A+ + + + + + + + +
5.200E-05 3.46E-04 +A+ + + + + + + + + +
5.600E-05 1.39E-04 + + + + + + + + + +
6.000E-05 6.29E-05 A+ + + + + + + + + +
6.400E-05 3.27E-05 A+ + + + + + + + + +
6.800E-05 2.04E-05 A+ + + + + + + + + +
7.200E-05 1.34E-05 A+ + + + + + + + + +
7.600E-05 7.17E-06 A+ + + + + + + + + +
8.000E-05 1.72E-05 A-----+-----+-----+-----+
8.400E-05 2.53E-05 A+ + + + + + + + + +
8.800E-05 4.51E-05 A+ + + + + + + + + +
9.200E-05 9.34E-05 A+ + + + + + + + + +
9.600E-05 2.20E-04 +A+ + + + + + + + +
1.000E-04 5.88E-04 +A+ + + + + + + + +

```

***** TRANSIENT ANALYSIS THOM= 27.000 TEMP= 27.000

```

TIME I(VIC2)
(A ) 0. 5.000E-03 1.000E-02 1.500E-02 2.000E-02
0. 6.58E-04 +A-----+-----+-----+-----+
4.000E-06 5.91E-12 A+ + + + + + + + +
8.000E-06 6.88E-12 A+ + + + + + + + +
1.200E-05 7.70E-12 A+ + + + + + + + +
1.600E-05 8.35E-12 A+ + + + + + + + +
2.000E-05 8.78E-12 A+ + + + + + + + +
2.400E-05 8.97E-12 A+ + + + + + + + +
2.800E-05 8.91E-12 A+ + + + + + + + +
3.200E-05 8.59E-12 A+ + + + + + + + +
3.600E-05 8.05E-12 A+ + + + + + + + +
4.000E-05 7.31E-12 A-----+-----+-----+-----+
4.400E-05 6.41E-12 A+ + + + + + + + +
4.800E-05 1.16E-10 A+ + + + + + + + +
5.200E-05 2.91E-03 +A+ + + + + + + + +
5.600E-05 7.54E-03 + + A+ + + + + + + +
6.000E-05 1.18E-02 + + + + A+ + + + + +
6.400E-05 1.55E-02 + + + + + +A+ + + +
6.800E-05 1.81E-02 + + + + + + +A+ + +
7.200E-05 1.96E-02 + + + + + + + +A+ +
7.600E-05 1.99E-02 + + + + + + + + +A
8.000E-05 1.90E-02 +-----+-----+-----+-----+
8.400E-05 1.69E-02 + + + + + + +A+ + +
8.800E-05 1.37E-02 + + + + + A+ + + + +
9.200E-05 9.75E-03 + + + A+ + + + + + +
9.600E-05 5.23E-03 + +A+ + + + + + + +
1.000E-04 6.58E-04 +A+ + + + + + + + +

```

***** TRANSIENT ANALYSIS THOM= 27.000 TEMP= 27.000

```

TIME I(VID2)
(A ) 0. 1.000E-04 2.000E-04 3.000E-04 4.000E-04
0. 8.23E-05 +-----+-----+-----+-----+
4.000E-06 7.58E-06 +A+ + + + + + + +
8.000E-06 6.61E-06 A+ + + + + + + + +
1.200E-05 1.55E-11 A+ + + + + + + + +
1.600E-05 1.68E-11 A+ + + + + + + + +
2.000E-05 1.77E-11 A+ + + + + + + + +
2.400E-05 1.80E-11 A+ + + + + + + + +
2.800E-05 1.79E-11 A+ + + + + + + + +
3.200E-05 1.73E-11 A+ + + + + + + + +
3.600E-05 1.62E-11 A+ + + + + + + + +
4.000E-05 1.47E-11 A-----+-----+-----+-----+
4.400E-05 1.14E-06 A+ + + + + + + + +
4.800E-05 2.88E-05 +A+ + + + + + + + +
5.200E-05 1.12E-04 + +A+ + + + + + + +
5.600E-05 1.69E-04 + + +A+ + + + + + +
6.000E-05 2.24E-04 + + + +A+ + + + + +
6.400E-05 2.71E-04 + + + + +A+ + + + +
6.800E-05 3.07E-04 + + + + + +A+ + + +
7.200E-05 3.29E-04 + + + + + + +A+ + +
7.600E-05 3.32E-04 + + + + + + + +A+ +
8.000E-05 3.20E-04 +-----+-----+-----+-----+
8.400E-05 2.91E-04 + + + + + +A+ + + +
8.800E-05 2.49E-04 + + + + + A+ + + + +
9.200E-05 1.97E-04 + + + + A+ + + + + +
9.600E-05 1.41E-04 + + +A+ + + + + + +
1.000E-04 8.23E-05 + +A+ + + + + + + +

```

***** TRANSIENT ANALYSIS THOM= 27.000 TEMP= 27.000

```

TIME V(10)
(A ) -1.000E+01 -5.000E+00 0. 5.000E+00 1.000E+01
0. -2.92E-02 +-----+-----+-----+-----+
4.000E-06 9.41E-01 + + + +A+ + + + +
8.000E-06 1.87E+00 + + + + +A+ + + + +
1.200E-05 2.70E+00 + + + + +A+ + + + +
1.600E-05 3.35E+00 + + + + +A+ + + + +
2.000E-05 3.78E+00 + + + + +A+ + + + +
2.400E-05 3.97E+00 + + + + +A+ + + + +
2.800E-05 3.90E+00 + + + + +A+ + + + +
3.200E-05 3.59E+00 + + + + +A+ + + + +
3.600E-05 3.05E+00 + + + + +A+ + + + +
4.000E-05 2.30E+00 +-----+-----+-----+-----+
4.400E-05 1.42E+00 + + + +A+ + + + +
4.800E-05 4.54E-01 + + + +A+ + + + +
5.200E-05 -5.34E-01 + + +A+ + + + + +
5.600E-05 -1.51E+00 + + + +A+ + + + +
6.000E-05 -2.40E+00 + + +A+ + + + + +3E+00
6.400E-05 -3.14E+00 + + +A+ + + + + +
6.800E-05 -3.67E+00 + + +A+ + + + + +
7.200E-05 -3.98E+00 + + +A+ + + + + +
7.600E-05 -4.04E+00 + + +A+ + + + + +
8.000E-05 -3.86E+00 +-----+-----+-----+-----+
8.400E-05 -3.43E+00 + + +A+ + + + + +
8.800E-05 -2.78E+00 + + +A+ + + + + +
9.200E-05 -1.97E+00 + + +A+ + + + + +
9.600E-05 -1.03E+00 + + +A+ + + + + +
1.000E-04 -2.92E-02 + + +A+ + + + + +

```

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(10)

DC COMPONENT = -4.173D-02

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	4.014E+00	1.000E+00	-6.743E-04	0.
2	2.000E+04	1.806E-03	4.499E-04	-9.748E+01	-9.748E+01
3	3.000E+04	7.591E-03	1.891E-03	1.795E+02	1.795E+02
4	4.000E+04	3.882E-03	9.670E-04	8.902E+01	8.902E+01
5	5.000E+04	6.219E-03	1.549E-03	1.783E+02	1.783E+02
6	6.000E+04	7.583E-04	1.889E-04	9.088E+01	9.088E+01
7	7.000E+04	7.987E-04	1.990E-04	1.702E+02	1.702E+02
8	8.000E+04	2.919E-03	7.272E-04	8.969E+01	8.969E+01
9	9.000E+04	1.627E-03	4.052E-04	-1.753E+02	-1.753E+02

TOTAL HARMONIC DISTORTION = 2.807E-01 PERCENT

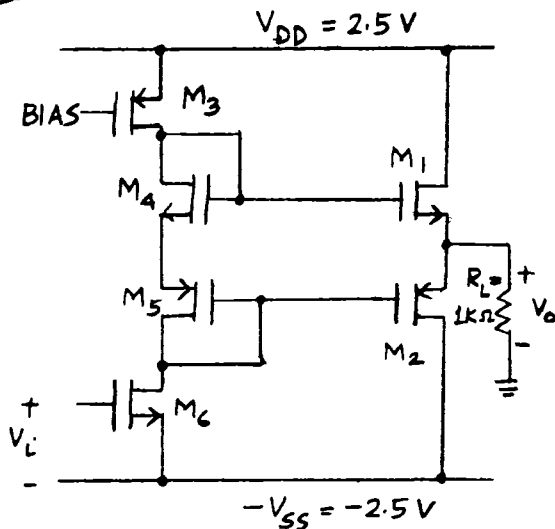
5.21

The negative limit on V_o is reached when M_6 reaches the edge of the active region

$$V_o^- = -V_{SS} + V_{OV_6} + V_{SG_2}$$

$$= -V_{SS} + V_{OV_6} - V_{GS_2}$$

and $V_{GS_2} < 0$, when M_2 conducts because M_2 is an enhancement-mode PMOS transistor.

5.22

$$\lambda_n = \frac{d\lambda_d}{dV_{ds}} / L = 0.08$$

$$\lambda_p = \frac{d\lambda_d}{dV_{ds}} / L = 0.04$$

$$\phi_{fn} = \frac{KT}{q} \ln \frac{4 \times 10^{15}}{1.45 \times 10^{10}} = 323 \text{ mV}$$

$$\phi_{fp} = \frac{KT}{q} \ln \frac{3 \times 10^{16}}{1.45 \times 10^{10}} = 375 \text{ mV}$$

$$2\phi_{fn} = 650 \text{ mV}$$

$$2\phi_{fp} = 750 \text{ mV}$$

Table (2.3)

$$\mu'_n = 127 \text{ } \mu\text{A/V} ; \mu'_p = 58 \text{ } \mu\text{A/V}$$

$$V_{tn} = 0.7 \text{ V} ; V_{tp} = -0.7 \text{ V}$$

$$C_{ox} = \frac{3.9 \times 8.854 \times 10^{-14}}{150 \times 10^{-8}} = 2.3 \frac{\text{fF}}{\mu\text{m}^2}$$

$$\gamma_n = \frac{\sqrt{2(1.6 \times 10^{-19}) 11.6 \times 8.86 \times 10^{-14} \times 4 \times 10^{15}}}{2.3 \times 10^{-7}}$$

$$= 0.158 \sqrt{\text{V}}$$

$$\gamma_p = \frac{\sqrt{2(1.6 \times 10^{-19}) 11.6 \times 8.86 \times 10^{-14} \times 3 \times 10^{16}}}{2.3 \times 10^{-7}}$$

$$= 0.432 \sqrt{\text{V}}$$

$$\text{For } V_o = 1 \text{ V}, V_{SB} = 1 + 2.5 = 3.5 \text{ V}$$

$$V_{t1} = 0.7 + 0.16 (\sqrt{0.65 + 3.5} - \sqrt{0.65})$$

$$= 0.9 \text{ V}$$

$$V_{OV_3} = \sqrt{\frac{2(10\mu)}{58(50)}} = 83 \text{ mV}$$

At peak output, we want

$$V_{GS1} = 2.5 - 0.083 - 1 = 1.417 \text{ V}$$

$$I_{D1} = \frac{\mu'_n}{2} \left(\frac{W}{L} \right)_1 (V_{GS1} - V_{t1})^2$$

$$I_{D1(\text{max})} = \frac{1 \text{ V}}{1 \text{ k}} = 1 \text{ mA}$$

$$\left(\frac{W}{L} \right)_1 = \frac{2 I_{D1}}{\mu'_n (V_{GS1} - V_{t1})^2} = \frac{2(1000)}{127(1.417 - 0.9)^2} = 59$$

$$\text{For } V_o = -1 \text{ V}, V_{SB} = -1 - 2.5 = -3.5 \text{ V}$$

$$V_{t2} = -0.7 - 0.43 (\sqrt{0.75 + 3.5} - \sqrt{0.75})$$

$$= -1.21 \text{ V}$$

$$V_{OV_6} = \sqrt{\frac{2(10)}{127(25)}} = 0.079 \text{ V}$$

At peak output, want

$$V_{GS_2} = -2.5 + 0.079 - (-1) = 1.421 \text{ V}$$

$$\left(\frac{W}{L}\right)_2 = \frac{2(1000)}{58(-1.421 + 1.21)^2} = 775$$

$$I_{d_4} = |I_{d_5}| = \frac{1}{10} I_{d_1}$$

$$\left(\frac{W}{L}\right)_4 = \frac{\left(\frac{W}{L}\right)_1}{10} = 5.9$$

$$\left(\frac{W}{L}\right)_5 = \frac{\left(\frac{W}{L}\right)_2}{10} = 77.5$$

COMPLEMENTARY SOURCE FOLLOWER CMOS OUTPUT STAGE

```
VDD 100 0 2.5
VSS 200 0 -2.5
RL 5 0 1K
M1 100 3 5 200 NMOS W=60U L=1U
M2 200 6 5 100 PMOS W=780U L=1U
M3 3 2 100 100 PMOS W=50U L=1U
M4 3 3 4 200 NMOS W=6U L=1U
M5 6 6 4 100 PMOS W=78U L=1U
M6 6 7 200 200 NMOS W=25U L=1U
```

* IN FIG. 5.31, THE BIAS VOLTAGE COULD BE ADJUSTED
 * BY TRIAL AND ERROR TO SET THE DRAIN CURRENT OF M3
 * EQUAL TO 10 MICROAMPS, BUT THIS PROCESS MAY REQUIRE
 * MANY ITERATIONS. SO INSTEAD, M7 AND IBIAS ARE ADDED
 * TO FORM A CURRENT MIRROR TO SET UP THE DC DRAIN
 * CURRENT IN M3.

```
M7 2 2 100 100 PMOS W=50U L=1U
IBIAS 2 200 9.9U
```

* THE DC INPUT IS ADJUSTED SO THAT
 * THE DC OUTPUT IS APPROXIMATELY ZERO.

```
VI 7 200 0.7761
```

```
.MODEL PMOS PMOS KP=58U LAMBDA=0.04 GAMMA=0.43 VTO=-0.7 LD=0
.MODEL NMOS NMOS KP=127U LAMBDA=0.08 GAMMA=0.16 VTO=0.7 LD=0
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.DC VI 0.76 0.79 0.001
.PLOT DC V(5)
.END
```

***** DC TRANSFER CURVES TNOM= 27.000 TEMP= 27.000

VOLT	V(5)						
(A)		-2.000E+00	-1.000E-00	0.	1.000E+00	2.000E+00	
7.600E-01	1.05E+00	+	+	+	+	+	+
7.610E-01	1.05E+00	+	+	+	+	+	+
7.620E-01	1.05E+00	+	+	+	+	+	+
7.630E-01	1.05E+00	+	+	+	+	+	+
7.640E-01	1.05E+00	+	+	+	+	+	+
7.650E-01	1.05E+00	+	+	+	+	+	+
7.660E-01	1.04E+00	+	+	+	+	+	+
7.670E-01	1.04E+00	+	+	+	+	+	+
7.680E-01	1.04E+00	+	+	+	+	+	+
7.690E-01	1.03E+00	+	+	+	+	+	+
7.700E-01	1.03E+00	+	+	+	+	+	+
7.710E-01	8.89E-01	+	+	+	+	+	+
7.720E-01	7.03E-01	+	+	+	+	+	+
7.730E-01	5.25E-01	+	+	+	+	+	+
7.740E-01	3.56E-01	+	+	+	+	+	+
7.750E-01	2.00E-01	+	+	+	+	+	+
7.760E-01	2.79E-02	+	+	+	+	+	+
7.770E-01	-1.56E-01	+	+	+	+	+	+
7.780E-01	-3.42E-01	+	+	+	+	+	+
7.790E-01	-5.27E-01	+	+	+	+	+	+
7.800E-01	-7.10E-01	+	+	+	+	+	+
7.810E-01	-8.91E-01	+	+	+	+	+	+
7.820E-01	-9.87E-01	+	+	+	+	+	+
7.830E-01	-9.92E-01	+	+	+	+	+	+
7.840E-01	-9.95E-01	+	+	+	+	+	+
7.850E-01	-9.97E-01	+	+	+	+	+	+
7.860E-01	-9.99E-01	+	+	+	+	+	+
7.870E-01	-1.00E+00	+	+	+	+	+	+
7.880E-01	-1.00E+00	+	+	+	+	+	+
7.890E-01	-1.00E+00	+	+	+	+	+	+
7.900E-01	-1.00E+00	+	+	+	+	+	+

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:2	= 1.718E+00	0:3	= 1.025E+00	0:4	= 1.048E-02
+0:5	= 9.746E-03	0:6	= -1.177E+00	0:7	= -1.723E+00
+0:100	= 2.500E+00	0:200	= -2.500E+00		

**** MOSFETS

SUBCKT

ELEMENT	0:M1	0:M2	0:M3	0:M4
MODEL	0:NMOS	0:PMOS	0:PMOS	0:NMOS
ID	1.139E-04	-1.041E-04	-1.017E-05	1.017E-05
IBS	-2.510E-14	2.490E-14	0.	-2.510E-14
IBD	-5.000E-14	5.000E-14	1.474E-14	-3.526E-14
VGS	1.016E+00	-1.187E+00	-7.814E-01	1.015E+00
VDS	2.490E+00	-2.509E+00	-1.474E+00	1.015E+00
VBS	-2.509E+00	2.490E+00	0.	-2.510E+00
VTH	8.582E-01	-1.122E+00	-7.000E-01	8.582E-01
VDSAT	1.579E-01	-6.468E-02	-8.137E-02	1.571E-01
BETA	9.138E-03	4.978E-02	3.071E-03	8.239E-04
GAM EFF	1.600E-01	4.300E-01	4.300E-01	1.600E-01
GM	1.443E-03	3.220E-03	2.499E-04	1.294E-04
GDS	7.596E-06	3.785E-06	3.840E-07	7.522E-07
GMB	6.544E-05	3.938E-04	6.936E-05	5.871E-06

SUBCKT

ELEMENT	0:M5	0:M6	0:M7
MODEL	0:PMOS	0:NMOS	0:PMOS
ID	-1.017E-05	1.017E-05	-9.900E-06
IBS	2.490E-14	0.	0.
IBD	3.678E-14	-1.322E-14	7.814E-15
VGS	-1.188E+00	7.761E-01	-7.814E-01
VDS	-1.188E+00	1.322E+00	-7.814E-01
VBS	2.489E+00	0.	0.
VTH	-1.122E+00	7.000E-01	-7.000E-01
VDSAT	-6.550E-02	7.610E-02	-8.137E-02
BETA	4.739E-03	3.511E-03	2.991E-03
GAM EFF	4.300E-01	1.600E-01	4.300E-01
GM	3.104E-04	2.672E-04	2.433E-04
GDS	3.882E-07	7.355E-07	3.840E-07
GMB	3.797E-05	2.759E-05	6.754E-05

5-23

Assume $M_2 = \text{off}$

$$\text{KCL } -I_{d1} = V_o/R_L$$

$$\text{From (5.112), } \frac{K'}{2} \frac{W}{L} (V_{gs} + V_t)^2 = V_o/R_L$$

$$\text{sub in (5.110), } \frac{K'}{2} \frac{W}{L} \left\{ -V_{ov} + A [V_o - (V_i - V_{osp})] \right\}^2 = \frac{V_o}{R_L}$$

$$\frac{K'}{2} \frac{W}{L} \left\{ V_{ov}^2 + A^2 [V_o - (V_i - V_{osp})]^2 - 2AV_{ov} [V_o - (V_i - V_{osp})] \right\} = \frac{V_o}{R_L}$$

$$\frac{K'}{2} \frac{W}{L} \left\{ V_{ov}^2 + A^2 [(V_o - V_i)^2 + V_{osp}^2 + 2(V_o - V_i)V_{osp}] - 2AV_{ov} [V_o - V_i + V_{osp}] \right\} = V_o/R_L$$

$$V_o^2 \left(\frac{K'}{2} \frac{W}{L} \right) A^2$$

$$+ V_o \left\{ \frac{K'}{2} \frac{W}{L} \left[-2V_i A^2 + 2V_{osp} A^2 - 2AV_{ov} \right] - \frac{1}{R_L} \right\}$$

$$+ \frac{K'}{2} \frac{W}{L} \left\{ V_{ov}^2 + V_i^2 A^2 + V_{osp}^2 A^2 - 2V_i V_{osp} A^2 + 2AV_{ov} V_i - 2AV_{ov} V_{osp} \right\} = 0$$

$$V_o = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$a = \frac{K'}{2} \frac{W}{L} A^2$$

$$b = \frac{K'}{2} \frac{W}{L} A^2 \left(-2V_i + V_{osp} - \frac{2V_{ov}}{A} \right) - \frac{1}{R_L}$$

$$c = \frac{K'}{2} \frac{W}{L} A^2 \left(V_i^2 + \frac{V_{ov}^2}{A^2} + V_{osp}^2 - 2V_i V_{osp} + \frac{2V_{ov} V_i}{A} - \frac{2V_{ov} V_{osp}}{A} \right)$$

$$b = -K' \frac{W}{L} A^2 \left(V_i + \frac{V_{ov}}{A} - V_{osp} \right) - \frac{1}{R_L}$$

$$b^2 = \left(K' \frac{W}{L} \right)^2 A^4 \left(V_i + \frac{V_{ov}}{A} - V_{osp} \right)^2 + \frac{1}{R_L^2} + 2K' \frac{W}{L} \frac{A^2}{R_L} \left(V_i + \frac{V_{ov}}{A} - V_{osp} \right)$$

$$4ac = \left(K' \frac{W}{L} \right)^2 A^4 \left(V_i^2 + \frac{V_{ov}^2}{A^2} + V_{osp}^2 - 2V_i V_{osp} + \frac{2V_{ov} V_i}{A} - \frac{2V_{ov} V_{osp}}{A} \right)$$

First term in b^2

$$= \left(K' \frac{W}{L} \right)^2 A^4 \left(V_i^2 + \frac{2V_i V_{ov}}{A} - 2V_i V_{osp} - \frac{2V_{ov} V_{osp}}{A} + \left(\frac{V_{ov}}{A} \right)^2 + V_{osp}^2 \right)$$

$$b^2 - 4ac = \left(\frac{1}{R_L} \right)^2 + 2K' \frac{W}{L} \frac{A^2}{R_L} \left(V_i + \frac{V_{ov}}{A} - V_{osp} \right)$$

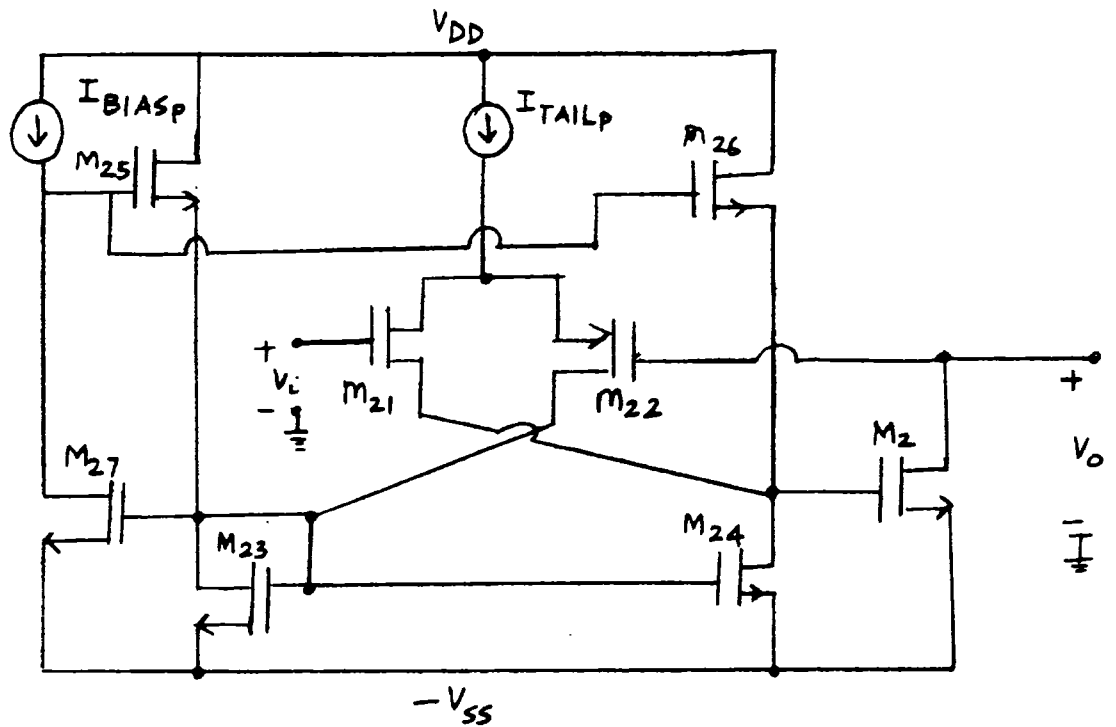
$$V_o = V_i + \frac{V_{ov}}{A} - V_{osp} + \frac{1}{K' \frac{W}{L} A^2 R_L} \pm \frac{1}{K' \frac{W}{L} A^2} \sqrt{\left(\frac{1}{R_L} \right)^2 + 2K' \frac{W}{L} \frac{A^2}{R_L} \left(V_i + \frac{V_{ov}}{A} - V_{osp} \right)}$$

V_o must be less than V_i

$$V_o = V_i + \frac{V_{ov}}{A} - V_{osp} + \frac{1}{\kappa' \frac{W}{L} A^2 R_L}$$

$$- \frac{1}{\kappa' \frac{W}{L} A^2} \sqrt{\frac{1}{R_L^2} + 2 \kappa' \frac{W}{L} \frac{A^2}{R_L} (V_i + \frac{V_{ov}}{A} - V_{osp})}$$

5.24



5.25

standby power

In Fig.(5.35),

$|I_{D17}| + |I_{D13}| + |I_{D14}|$ flows from V_{DD} to $-V_{SS}$. $|I_{D1}|$ flows from V_{DD} to M_2 in Problem (5.24)

In Problem (5.24),

$I_{D27} + I_{D23} + I_{D24}$ flows from V_{DD} to $-V_{SS}$. I_{D2} flows from M_1 in fig(5.35) to $-V_{SS}$

Therefore, the standby power dissipation is,

$$\begin{aligned} & [|I_{D17}| + |I_{D13}| + |I_{D14}|] [V_{DD} - (-V_{SS})] \\ & + [I_{D27} + I_{D23} + I_{D24}] [V_{DD} - (-V_{SS})] \\ & + |I_{D1}| [V_{DD} - (-V_{SS})] \leq 70 \text{ mW} \end{aligned}$$

From (a) and (e),

$$\left[\frac{|I_{D1}|}{100} + \frac{|I_{D1}|}{10} + \frac{|I_{D1}|}{10} + \frac{I_{D2}}{100} + \frac{I_{D2}}{10} \right]$$

$$\frac{I_{D2}}{10} + |I_{D1}| \leq 70 \text{ mW}$$

Also in standby $V_i = V_o = 0$, so $I_{RL} = 0$ and $|I_{D1}| = I_{D2}$

$$|I_{D1}| [1 + 0.4 + 0.02] \leq 70 \text{ mW}$$

$$|I_{D1}| \leq 9.9 \text{ mA} \approx 10 \text{ mA}$$

Use max standby current to minimize distortion

$$|I_{D17}| = \frac{|I_{D1}|}{100} = 99 \mu\text{A} \approx 100 \mu\text{A} \approx I_{BIAS}$$

$$|I_{D13}| = |I_{D14}| = \frac{9.9 \text{ mA}}{10} = 990 \mu\text{A} \approx 1 \text{ mA}$$

$$I_{TAIL} = 5 I_{BIAS} = 500 \mu\text{A}$$

$$I_{D27} = \frac{I_{D2}}{100} = 99 \mu\text{A} \approx 100 \mu\text{A} = I_{BIASP}$$

$$I_{D23} = I_{D24} = \frac{9.9 \text{ mA}}{10} = 990 \mu\text{A} \approx 1 \text{ mA}$$

$$I_{TAILP} = 5 I_{BIASP} = 500 \mu\text{A}$$

Gain Error $\leq 1\%$

$$\text{From (5.117), } \frac{1}{2A g_m R_L} \leq 0.01$$

To minimize distortion, use the maximum allowed error-amplifier gain = 5

$$\begin{aligned} g_{m1} & \geq \frac{1}{2A R_L (0.01)} = \frac{1}{2(5)(100)(0.01)} \\ & = 0.1 \frac{\text{A}}{\text{V}} = 100,000 \frac{\mu\text{A}}{\text{V}} \end{aligned}$$

$$g_{m1} = \sqrt{2 K'_p \left(\frac{W}{L} \right)_1 |I_{D1}|}$$

From Table (2.3),

$$C_{ox} = \frac{3.9 \times 8.86 \times 10^{-14}}{150 \times 10^{-8}} = 2.3 \times 10^{-7} \frac{\text{F}}{\text{cm}^2}$$

$$K'_p = 2.3 \times 10^{-7} \times 250 \frac{\text{cm}^2}{\text{V} \cdot \text{s}} = 58 \mu\text{A}/\text{V}^2$$

$$\sqrt{2(58) \left(\frac{W}{L} \right)_1 (10000 \mu\text{A})} > 100,000$$

$$\left(\frac{W}{L} \right)_1 \geq 8620 \approx 8700$$

$$\left(\frac{W}{L} \right)_{17} = \frac{\left(\frac{W}{L} \right)_1}{100} = 87$$

$$\left(\frac{W}{L} \right)_{13} = \left(\frac{W}{L} \right)_{14} = \frac{\left(\frac{W}{L} \right)_1}{10} = 870$$

similarly,

$$g_{m2} = \sqrt{2 \kappa'_n \left(\frac{W}{L}\right)_2 I_{D2}}$$

$$\kappa'_n = 2.3 \times 10^{-7} \times 550 \frac{\text{cm}^2}{\text{V}\cdot\text{s}} = 127 \mu\text{A}/\text{V}^2$$

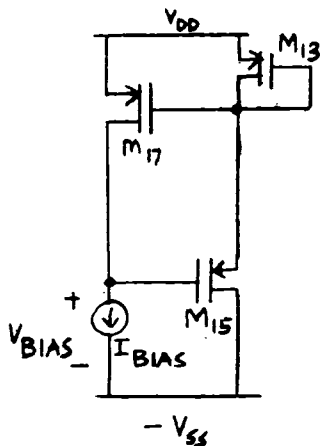
$$\sqrt{2(127) \left(\frac{W}{L}\right)_2 (10000 \mu\text{A})} > 100,000$$

$$\left(\frac{W}{L}\right)_2 > 3940 \approx 4000$$

$$\left(\frac{W}{L}\right)_{27} = \frac{\left(\frac{W}{L}\right)_2}{100} = 40$$

$$\left(\frac{W}{L}\right)_{23} = \left(\frac{W}{L}\right)_{24} = \frac{\left(\frac{W}{L}\right)_2}{10} = 400$$

Let V_{BIAS} = voltage across I_{BIAS}



$$V_{\text{BIAS}} = \underbrace{V_{\text{DD}} - (-V_{\text{SS}})}_{2.5 - (-2.5)} - \underbrace{|V_{\text{GS17}}|}_{0.7} - \underbrace{|V_{\text{GS15}}|}_{\sqrt{\frac{2I_{\text{BIAS}}}{\kappa_p \left(\frac{W}{L}\right)_{17}}}}_{\sqrt{\frac{2(100)}{58(87)}} = 0.2} \geq 0.5$$

$|V_{\text{GS15}}|$ is max. when $|I_{\text{D15}}|$ is max

That is when $I_{\text{D12}} = 0$

So, $|I_{\text{D15}}|_{\text{max}} = |I_{\text{D13}}| = 1 \text{ mA}$

Note: this worst case condition may not occur in practice because m_{12} may not turn off completely

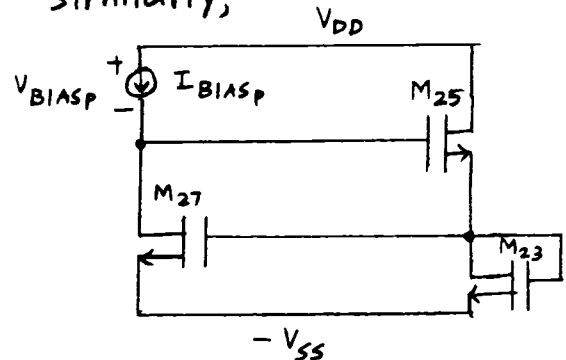
$$|V_{\text{GS15}}|_{\text{max}} = \underbrace{|V_{\text{t15}}|}_{0.7} + \underbrace{\sqrt{\frac{2|I_{\text{D15}}|_{\text{max}}}{\kappa'_p \left(\frac{W}{L}\right)_{15}}}}_{\sqrt{\frac{2(1000)}{58 \left(\frac{W}{L}\right)_{15}}}}$$

$$5 - 0.7 - 0.2 - 0.7 - \sqrt{\frac{2(1000)}{58 \left(\frac{W}{L}\right)_{15}}} \geq 0.5 \text{ V}$$

$$\sqrt{\frac{2(1000)}{58 \left(\frac{W}{L}\right)_{15}}} \leq 2.9 \text{ V}$$

$$\left(\frac{W}{L}\right)_{15} \geq \frac{2(1000)}{58(2.9)^2} = 4.1 \approx 4$$

similarly,



$$V_{\text{BIASp}} = V_{\text{DD}} - [-V_{\text{SS}} + V_{\text{GS27}} + V_{\text{GS25}}] \geq 0.5 \text{ V}$$

$$V_{\text{OV27}} = \sqrt{\frac{2(100)}{127(40)}} = 0.2 \text{ V}$$

$$V_{\text{OV25(max.)}} = \sqrt{\frac{2(10)I_{\text{BIAS}}}{\left(\frac{W}{L}\right)_{25} 127}} \text{ When } |I_{\text{D22}}| = 0$$

$$5 - 0.7 - 0.2 - 0.7 - \sqrt{\frac{2(1000)}{127 \left(\frac{W}{L}\right)_{25}}} \geq 0.5 \text{ V}$$

$$\left(\frac{W}{L}\right)_{25} > \frac{2(1000)}{127(2.9)^2} = 1.9 \approx 2$$

Error amplifier gain

From (5.141) for the top amp

$$A = \frac{g_{m11}}{g_{m16}} \quad (\text{ignore body effect})$$

$$A = 5 = \sqrt{\frac{2(I_{TAIL/2}) \mu_n (W/L)_{11}}{2(|I_{D14}| - I_{TAIL/2}) \mu_p (W/L)_{16}}}$$

$$= \sqrt{\frac{250(127)(W/L)_{11}}{750(58)(W/L)_{16}}} = \sqrt{\frac{0.73(W/L)_{11}}{(W/L)_{16}}}$$

$$\text{But, } (W/L)_{16} = (W/L)_{15} = 4$$

$$\text{So, } (W/L)_{11} = \frac{A^2 (W/L)_{16}}{0.73} = \frac{25(4)}{0.73} = 137 \approx 140$$

similarly, for the bottom amp,

$$A = \frac{g_{m21}}{g_{m26}}$$

$$A = 5 = \sqrt{\frac{2(I_{TAILP/2}) \mu_p (W/L)_{21}}{2(I_{D24} - I_{TAILP/2}) \mu_n (W/L)_{26}}}$$

$$= \sqrt{\frac{(250)(57)(W/L)_{21}}{(750)(127)(W/L)_{26}}} = \sqrt{\frac{0.15(W/L)_{21}}{(W/L)_{26}}}$$

$$\text{But, } (W/L)_{26} = (W/L)_{25} = 2$$

$$\text{So, } (W/L)_{21} = \frac{A^2 (W/L)_{26}}{0.15} = \frac{25(2)}{0.15} = 333 \approx 300$$

CMOS CLASS A/B OUTPUT STAGE

```

VDD      100      0      2.5
VSS      200      0      -2.5
M1       2       14    100 100 CMOSF L=1U W=8700U
M11      14      1     18 18  CMOSF L=1U W=140U
M12      13      2     18 18  CMOSF L=1U W=140U
M13      13     13    100 100 CMOSF L=1U W=870U
M14      14     13    100 100 CMOSF L=1U W=870U
M15      200     17     13 13  CMOSF L=1U W=4U
M16      200     17     14 14  CMOSF L=1U W=4U
M17      17     13    100 100 CMOSF L=1U W=87U

M2       2       24    200 200 CMOSF L=1U W=4000U
M21      24      1     28 28  CMOSF L=1U W=330U
M22      23      2     28 28  CMOSF L=1U W=330U
M23      23     23    200 200 CMOSF L=1U W=400U
M24      24     23    200 200 CMOSF L=1U W=400U
M25      100     27     23 23  CMOSF L=1U W=2U
M26      100     27     24 24  CMOSF L=1U W=2U
M27      27     23    200 200 CMOSF L=1U W=40U

```

.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0M VTO=0.7 KP=127U

.MODEL CMOSF PMOS LEVEL=1 LAMBDA=0M VTO=-0.7 KP=58U

```

IBIASN   17      200 99U
IBIASP   100     27 99U

```

```

ITAILN   18      200 495U
ITAILP   100     28 495U

```

VIN 1 0 0 AC 1

RLOAD 2 0 100

.OPTIONS NOPAGE NOMOD

.WIDTH OUT=80

.OP

.DC VIN -2.5 2.5 0.1

.PLOT DC V(2)

* PRINT VOLTAGES ACROSS IDEAL CURRENT SOURCES

.PRINT V(17, 200) V(18, 200) V(100, 27) V(100, 28)

.TF V(2) VIN

.AC DEC 1 1 10

.PRINT AC VM(2, 1) VM(2) VM(1)

.END

***** DC TRANSFER CURVES TNO= 27.000 TEMP= 27.000

```

      VOLT      V(2)
(A)      -4.000E+00 -2.000E+00 0. 2.000E+00 4.000E+00
      +      +      +      +      +
-2.500E+00 -2.28E+00 +-----A-----+-----+-----+-----+
-2.400E+00 -2.27E+00 + + A + + + + + + + +
-2.300E+00 -2.25E+00 + + A + + + + + + + +
-2.200E+00 -2.17E+00 + + A+ + + + + + + +
-2.100E+00 -2.07E+00 + + A+ + + + + + + +
-2.000E+00 -1.98E+00 + + A + + + + + + + +
-1.900E+00 -1.88E+00 + + +A + + + + + + + +
-1.800E+00 -1.78E+00 + + + A + + + + + + + +
-1.700E+00 -1.68E+00 + + + A + + + + + + + +
-1.600E+00 -1.58E+00 + + + A + + + + + + + +
-1.500E+00 -1.48E+00 +-----A-----+-----+-----+
-1.400E+00 -1.38E+00 + + + A + + + + + + + +
-1.300E+00 -1.28E+00 + + + A + + + + + + + +
-1.200E+00 -1.18E+00 + + + A+ + + + + + + +
-1.100E+00 -1.08E+00 + + + A+ + + + + + + +
-1.000E+00 -9.90E-01 + + + A + + + + + + + +
-9.000E-01 -8.91E-01 + + + +A + + + + + + + +
-8.000E-01 -7.92E-01 + + + +A + + + + + + + +
-7.000E-01 -6.93E-01 + + + +A + + + + + + + +
-6.000E-01 -5.94E-01 + + + + A + + + + + + + +
-5.000E-01 -4.95E-01 +-----A-----+-----+-----+
-4.000E-01 -3.96E-01 + + + + A + + + + + + + +
-3.000E-01 -2.97E-01 + + + + A + + + + + + + +
-2.000E-01 -1.98E-01 + + + + A+ + + + + + + +
-1.000E-01 -9.90E-02 + + + + A+ + + + + + + +
0. 0. + + + + A + + + + + + + +
1.000E-01 9.90E-02 + + + + +A + + + + + + + +
2.000E-01 1.98E-01 + + + + +A + + + + + + + +
3.000E-01 2.97E-01 + + + + + A + + + + + + + +
4.000E-01 3.96E-01 + + + + + A + + + + + + + +
5.000E-01 4.95E-01 +-----A-----+-----+-----+
6.000E-01 5.94E-01 + + + + + A + + + + + + + +
7.000E-01 6.93E-01 + + + + + A+ + + + + + + +
8.000E-01 7.92E-01 + + + + + A+ + + + + + + +
9.000E-01 8.91E-01 + + + + + A+ + + + + + + +
1.000E+00 9.90E-01 + + + + + A + + + + + + + +
1.100E+00 1.08E+00 + + + + + +A + + + + + + + +
1.200E+00 1.18E+00 + + + + + +A + + + + + + + +
1.300E+00 1.28E+00 + + + + + + A + + + + + + + +
1.400E+00 1.38E+00 + + + + + + A + + + + + + + +
1.500E+00 1.48E+00 +-----A-----+-----+-----+
1.600E+00 1.58E+00 + + + + + + A + + + + + + + +
1.700E+00 1.68E+00 + + + + + + A + + + + + + + +
1.800E+00 1.78E+00 + + + + + + A + + + + + + + +
1.900E+00 1.88E+00 + + + + + + A+ + + + + + + +
2.000E+00 1.98E+00 + + + + + + A + + + + + + + +
2.100E+00 2.07E+00 + + + + + + +A + + + + + + + +
2.200E+00 2.17E+00 + + + + + + +A + + + + + + + +
2.300E+00 2.25E+00 + + + + + + + A + + + + + + + +
2.400E+00 2.27E+00 + + + + + + + A + + + + + + + +
2.500E+00 2.28E+00 +-----A-----+-----+-----+
      +      +      +      +      +

```

VOLT	VOLTAGE 17 200	VOLTAGE 18 200	VOLTAGE 100 27	VOLTAGE 100 28
-2.5000E+00	1.327E+00	-7.218E-01	9.252E-01	3.938E+00
-2.4000E+00	1.181E+00	-6.929E-01	9.280E-01	3.927E+00
-2.3000E+00	9.983E-01	-6.404E-01	9.327E-01	3.900E+00
-2.2000E+00	9.274E-01	-5.556E-01	9.311E-01	3.828E+00
-2.1000E+00	9.247E-01	-4.562E-01	9.334E-01	3.729E+00
-2.0000E+00	9.221E-01	-3.567E-01	9.358E-01	3.629E+00
-1.9000E+00	9.196E-01	-2.572E-01	9.383E-01	3.530E+00
-1.8000E+00	9.171E-01	-1.578E-01	9.407E-01	3.430E+00
-1.7000E+00	9.145E-01	-5.827E-02	9.431E-01	3.331E+00
-1.6000E+00	9.120E-01	4.121E-02	9.455E-01	3.231E+00
-1.5000E+00	9.095E-01	1.407E-01	9.480E-01	3.132E+00
-1.4000E+00	9.070E-01	2.402E-01	9.504E-01	3.032E+00
-1.3000E+00	9.044E-01	3.397E-01	9.528E-01	2.932E+00
-1.2000E+00	9.019E-01	4.392E-01	9.552E-01	2.833E+00
-1.1000E+00	8.994E-01	5.386E-01	9.577E-01	2.733E+00
-1.0000E+00	8.969E-01	6.381E-01	9.601E-01	2.634E+00
-9.0000E-01	8.944E-01	7.376E-01	9.626E-01	2.534E+00
-8.0000E-01	8.919E-01	8.371E-01	9.650E-01	2.435E+00
-7.0000E-01	8.894E-01	9.366E-01	9.675E-01	2.335E+00
-6.0000E-01	8.869E-01	1.036E+00	9.699E-01	2.236E+00
-5.0000E-01	8.844E-01	1.135E+00	9.723E-01	2.136E+00
-4.0000E-01	8.819E-01	1.235E+00	9.748E-01	2.037E+00
-3.0000E-01	8.794E-01	1.334E+00	9.773E-01	1.937E+00
-2.0000E-01	8.769E-01	1.434E+00	9.797E-01	1.838E+00
-1.0000E-01	8.744E-01	1.533E+00	9.822E-01	1.738E+00
0.	8.719E-01	1.633E+00	9.846E-01	1.639E+00
1.0000E-01	8.694E-01	1.732E+00	9.871E-01	1.539E+00
2.0000E-01	8.670E-01	1.832E+00	9.896E-01	1.440E+00
3.0000E-01	8.645E-01	1.931E+00	9.920E-01	1.340E+00
4.0000E-01	8.620E-01	2.031E+00	9.945E-01	1.241E+00
5.0000E-01	8.595E-01	2.130E+00	9.970E-01	1.141E+00
6.0000E-01	8.571E-01	2.230E+00	9.994E-01	1.042E+00
7.0000E-01	8.546E-01	2.329E+00	1.001E+00	9.427E-01
8.0000E-01	8.521E-01	2.429E+00	1.004E+00	8.432E-01
9.0000E-01	8.497E-01	2.528E+00	1.006E+00	7.437E-01
1.0000E+00	8.472E-01	2.628E+00	1.009E+00	6.442E-01
1.1000E+00	8.448E-01	2.727E+00	1.011E+00	5.447E-01
1.2000E+00	8.423E-01	2.827E+00	1.014E+00	4.452E-01
1.3000E+00	8.399E-01	2.926E+00	1.016E+00	3.457E-01
1.4000E+00	8.374E-01	3.026E+00	1.019E+00	2.462E-01
1.5000E+00	8.350E-01	3.125E+00	1.021E+00	1.467E-01
1.6000E+00	8.325E-01	3.225E+00	1.024E+00	4.723E-02
1.7000E+00	8.301E-01	3.325E+00	1.026E+00	-5.225E-02
1.8000E+00	8.277E-01	3.424E+00	1.029E+00	-1.517E-01
1.9000E+00	8.252E-01	3.524E+00	1.031E+00	-2.512E-01
2.0000E+00	8.228E-01	3.623E+00	1.034E+00	-3.507E-01
2.1000E+00	8.204E-01	3.723E+00	1.036E+00	-4.502E-01
2.2000E+00	8.180E-01	3.822E+00	1.039E+00	-5.496E-01
2.3000E+00	8.157E-01	3.894E+00	1.109E+00	-6.344E-01
2.4000E+00	8.147E-01	3.921E+00	1.288E+00	-6.870E-01
2.5000E+00	8.118E-01	3.933E+00	1.424E+00	-7.150E-01

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

MODE	=VOLTAGE	MODE	=VOLTAGE	MODE	=VOLTAGE
+0:1	= 0.	0:2	=-1.697E-08	0:13	= 1.601E+00
+0:14	= 1.601E+00	0:17	=-1.628E+00	0:18	=-8.669E-01
+0:23	=-1.602E+00	0:24	=-1.602E+00	0:27	= 1.515E+00
+0:28	= 8.608E-01	0:100	= 2.500E+00	0:200	=-2.500E+00

**** MOSFETS

SUBCKT	0:M1	0:M11	0:M12	0:M13
MODEL	0:CMOSP	0:CMOSP	0:CMOSP	0:CMOSP
ID	-9.900E-03	2.475E-04	2.475E-04	-9.900E-04
IBS	0.	0.	0.	0.
IBD	2.500E-14	-2.469E-14	-2.469E-14	8.981E-15
VGS	-8.981E-01	8.669E-01	8.669E-01	-8.981E-01
VDS	-2.500E+00	2.468E+00	2.468E+00	-8.981E-01
VBS	0.	0.	0.	0.
VTH	-7.000E-01	7.000E-01	7.000E-01	-7.000E-01
VDSAT	-1.981E-01	1.669E-01	1.669E-01	-1.981E-01
BETA	5.046E-01	1.778E-02	1.778E-02	5.046E-02
GAM EFF	0.	0.	0.	0.
GM	9.996E-02	2.967E-03	2.967E-03	9.996E-03
GDS	0.	0.	0.	0.
GMB	0.	0.	0.	0.

SUBCKT	0:M14	0:M15	0:M16	0:M17
MODEL	0:CMOSP	0:CMOSP	0:CMOSP	0:CMOSP
ID	-9.900E-04	-7.425E-04	-7.425E-04	-9.900E-05
IBS	0.	0.	0.	0.
IBD	8.981E-15	4.102E-14	4.102E-14	4.128E-14
VGS	-8.981E-01	-3.230E+00	-3.230E+00	-8.981E-01
VDS	-8.981E-01	-4.101E+00	-4.101E+00	-4.128E+00
VBS	0.	0.	0.	0.
VTH	-7.000E-01	-7.000E-01	-7.000E-01	-7.000E-01
VDSAT	-1.981E-01	-2.530E+00	-2.530E+00	-1.981E-01
BETA	5.046E-02	2.320E-04	2.320E-04	5.046E-03
GAM EFF	0.	0.	0.	0.
GM	9.996E-03	5.870E-04	5.870E-04	9.996E-04
GDS	0.	0.	0.	0.
GMB	0.	0.	0.	0.

SUBCKT	0:M2	0:M21	0:M22	0:M23
MODEL	0:CMOSP	0:CMOSP	0:CMOSP	0:CMOSP
ID	9.900E-03	-2.475E-04	-2.475E-04	9.900E-04
IBS	0.	0.	0.	0.
IBD	-2.500E-14	2.463E-14	2.463E-14	-8.974E-15
VGS	8.974E-01	-8.608E-01	-8.608E-01	8.974E-01
VDS	2.500E+00	-2.463E+00	-2.463E+00	8.974E-01
VBS	0.	0.	0.	0.
VTH	7.000E-01	-7.000E-01	-7.000E-01	7.000E-01
VDSAT	1.974E-01	-1.608E-01	-1.608E-01	1.974E-01
BETA	5.080E-01	1.914E-02	1.914E-02	5.080E-02
GAM EFF	0.	0.	0.	0.
GM	1.003E-01	3.078E-03	3.078E-03	1.003E-02
GDS	0.	0.	0.	0.
GMB	0.	0.	0.	0.

SUBCKT	0:M24	0:M25	0:M26	0:M27
MODEL	0:CMOSP	0:CMOSP	0:CMOSP	0:CMOSP
ID	9.900E-04	7.425E-04	7.425E-04	9.900E-05
IBS	0.	0.	0.	0.
IBD	-8.974E-15	-4.103E-14	-4.103E-14	-4.015E-14
VGS	8.974E-01	3.117E+00	3.117E+00	8.974E-01
VDS	8.974E-01	4.102E+00	4.102E+00	4.015E+00
VBS	0.	0.	0.	0.
VTH	7.000E-01	7.000E-01	7.000E-01	7.000E-01
VDSAT	1.974E-01	2.417E+00	2.417E+00	1.974E-01
BETA	5.080E-02	2.540E-04	2.540E-04	5.080E-03
GAM EFF	0.	0.	0.	0.
GM	1.003E-02	6.142E-04	6.142E-04	1.003E-03
GDS	0.	0.	0.	0.
GMB	0.	0.	0.	0.

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

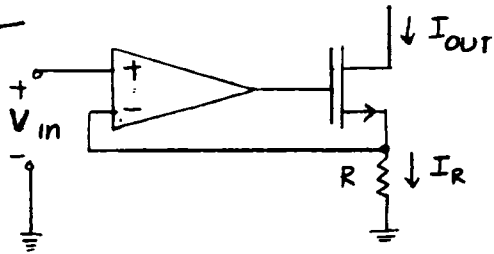
V(2)/VIN	= 9.902E-01
INPUT RESISTANCE AT VIN	= 1.000E+20
OUTPUT RESISTANCE AT V(2)	= 9.825E-01

***** AC ANALYSIS TNOM= 27.000 TEMP= 27.000

FREQ	VOLTAGE M 2	VOLTAGE M 2	VOLTAGE M 1
1.0000E+00	9.825E-03	9.902E-01	1.000E+00
1.0000E+01	9.825E-03	9.902E-01	1.000E+00

CHAPTER 6

6.1

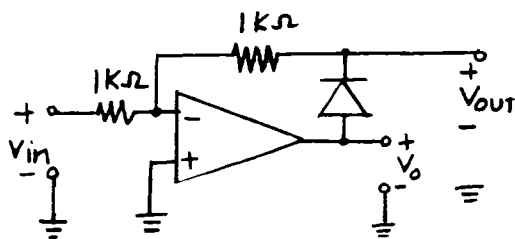


For ideal opamp,

$$I_R = \frac{V_{in}}{R} = I_{OUT}$$

$$\Rightarrow I_{OUT} = \frac{V_{in}}{R}$$

6.2



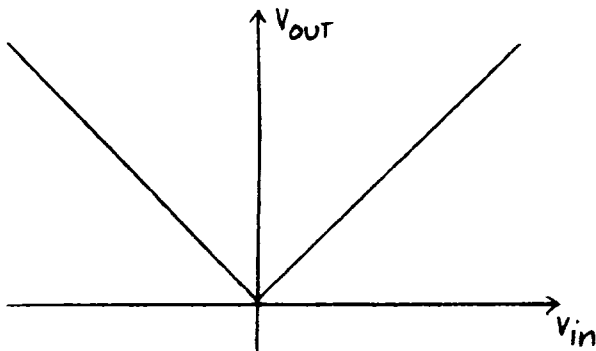
For V_{in} positive, V_o is negative, diode is reverse biased and

$$V_{OUT} = V_{in}$$

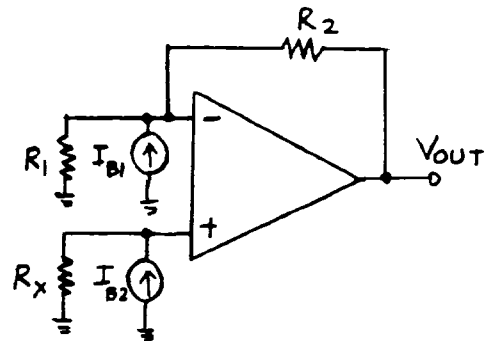
For V_{in} negative, V_o is positive,

After the diode turns on, we

$$\text{have } V_{OUT} = -V_{in}$$



6.3



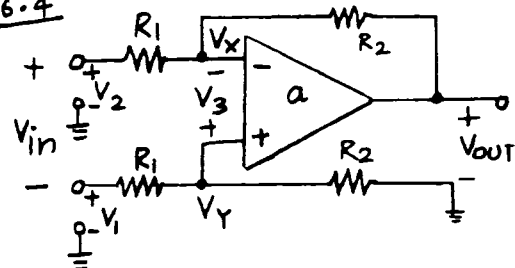
$$V_{OUT} \cong -R_2 I_{B1} + \frac{R_2 + R_1}{R_1} I_{B2} R_x$$

If $I_{B1} = I_{B2}$, then $V_{OUT} = 0$, when

$$R_2 = \frac{R_2 + R_1}{R_1} R_x$$

$$\therefore R_x = \frac{R_1 R_2}{R_1 + R_2} = R_1 \parallel R_2$$

6.4



$$V_3 = \frac{V_{OUT}}{a}, \quad V_Y = \frac{R_2}{R_1 + R_2} V_1$$

$$V_X = V_Y - V_3 = \frac{R_2}{R_1 + R_2} V_1 - \frac{V_{OUT}}{a} \rightarrow (1)$$

$$\frac{V_2 - V_X}{R_1} = \frac{V_X - V_{OUT}}{R_2} \rightarrow (2)$$

Eliminating V_X from (1) & (2),

$$A_v = \frac{V_{OUT}}{V_2 - V_1} = \frac{V_{OUT}}{V_{in}}$$

$$= \frac{-R_2/R_1}{1 + \frac{1}{a} \left(1 + \frac{R_2}{R_1} \right)} \rightarrow (3)$$

Require, $A_v \geq 999$ when a change -50% . From (3) the new gain value after a change is,

$$A'_v = \frac{-R_2/R_1}{1 + \frac{(1 + R_2/R_1)}{1/2 a}}$$

$$\approx -\frac{R_2}{R_1} \left[1 - \frac{2}{a} \left(1 + \frac{R_2}{R_1} \right) \right]$$

change from nominal is,

$$A'_v - A_v = \Delta A_v = \frac{1}{a} \left(1 + \frac{R_2}{R_1} \right) \frac{R_2}{R_1}$$

for $\frac{R_2}{R_1} \approx 1000$, we require

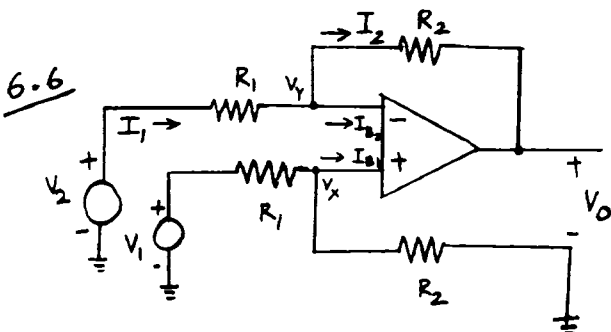
$$\Delta A_v \leq 1 \quad \therefore a \geq 10^6$$

6.5 $CMRR = \left(\frac{\Delta V_{os}}{\Delta V_{ic}} \right)^{-1}$

(from (6.48))

For $\Delta V_{ic} = 10V - (-10V) = 20V$,
we require $\Delta V_{os} \leq 1mV$

$$\therefore CMRR \geq \left[\frac{10^{-3}}{20} \right] = 86 \text{ dB}$$



With $V_1 = V_2 = 0$

① $V_x = -I_{B1} (R_1 \parallel R_2) = V_Y$ (virtual null)

② $I_1 = \frac{0 - V_Y}{R_1} = I_{B2} + I_2$

$$\Rightarrow I_2 = -\frac{V_Y}{R_1} - I_{B2}$$

③ $V_o = V_Y - I_2 R_2$

$$= V_x + \left(\frac{V_Y}{R_1} + I_{B2} \right) R_2$$

$$= V_x \left(1 + \frac{R_2}{R_1} \right) + I_{B2} R_2$$

$$= -I_{B1} \frac{R_1 R_2}{R_1 + R_2} \left(\frac{R_1 + R_2}{R_1} \right) + I_{B2} R_2$$

$$= (I_{B2} - I_{B1}) R_2 = -I_{os} R_2$$

$$|I_{os}| = 100 \text{ nA}$$

$$V_o = (100 \text{ nA}) R_2 \leq 10 \text{ mV}$$

$$R_2 \leq \frac{10 \text{ mV}}{100 \text{ nA}} = 100 \text{ k}\Omega$$

Also, gain $= -\frac{R_2}{R_1} = -10$

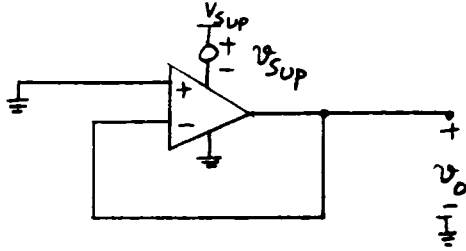
$$R_1 = \frac{R_2}{10} \leq 10 \text{ k}\Omega$$

One solution:

$$R_1 = 10 \text{ k}\Omega \quad R_2 = 100 \text{ k}\Omega$$

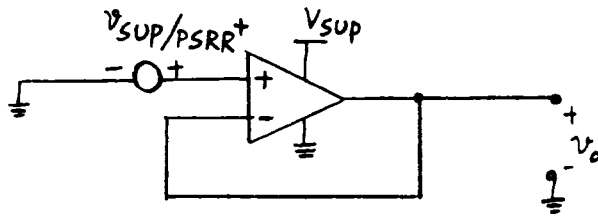
6.7

original connection:



$$v_o = A^+ v_{sup}$$

The same output can be obtained in the following configuration



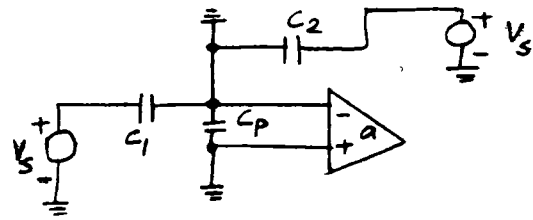
$$\text{From (6.51), } PSRR^+ = \frac{A_{dm}}{A^+}$$

$$v_o = \frac{v_{sup}}{PSRR^+} A_{dm}$$

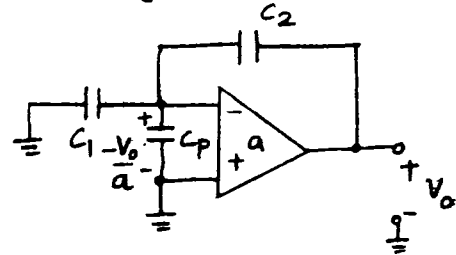
In the voltage follower configuration, $A_{dm} = 1$.

$$\text{So, } v_o = \frac{v_{sup}}{PSRR^+} (1)$$

$$\text{Therefore, peak output} = \frac{v_{sup}}{PSRR^+} = \frac{20}{10} \text{ mV} = 2 \text{ mV}$$

During ϕ_1 ,

$$Q_1 = v_s C_1 + v_s C_2$$

During ϕ_2 ,

$$Q_2 = \left(0 + \frac{v_o}{a}\right) C_1 + \left(0 + \frac{v_o}{a}\right) C_p + \left(v_o + \frac{v_o}{a}\right) C_2$$

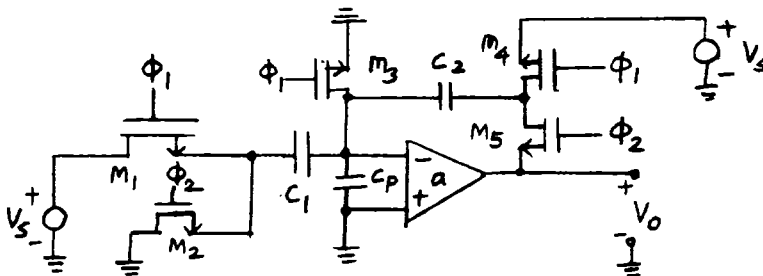
From charge conservation,

$$Q_1 = Q_2$$

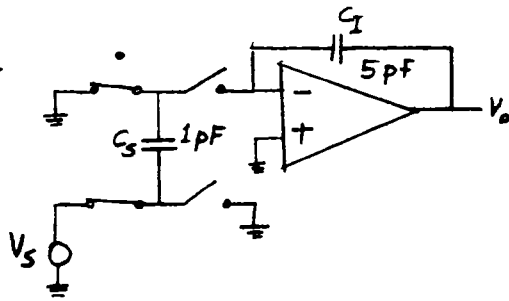
$$v_s (C_1 + C_2) = v_o \left(\frac{C_1}{a} + \frac{C_p}{a} + C_2 + \frac{C_2}{a} \right)$$

$$v_o = \frac{v_s (C_1 + C_2)}{C_2 + \frac{C_1 + C_p + C_2}{a}}$$

6.8



6.9

Each cycle on C_s

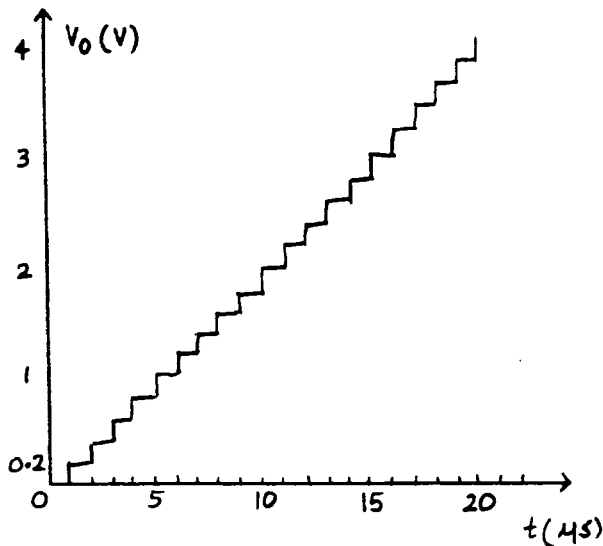
$$Q = C_s V_s = 1 \text{ pF} (1 \text{ V}) = 1 \text{ pC}$$

transfer to C_I

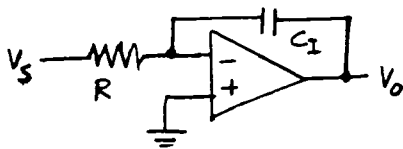
$$Q = C_I V_o$$

$$1 \text{ pC} = 5 \text{ pF } V_o$$

$$0.2 \text{ V} = V_o \text{ (per step)}$$



(b) continuous time

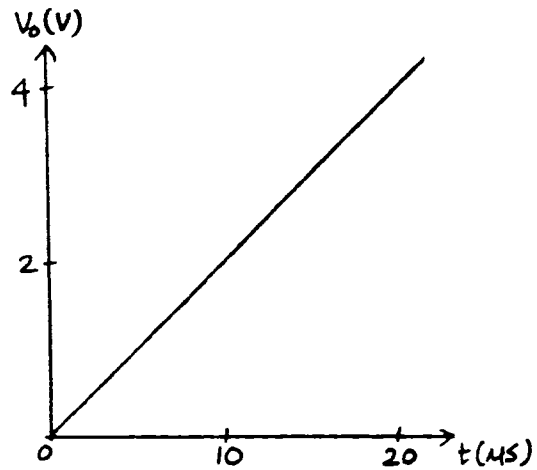


$$R = \frac{1}{f C_s}$$

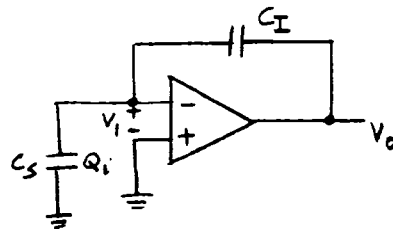
$$\frac{V_o}{V_s} = \frac{1}{R C_I s} = \frac{C_s}{C_I} \frac{f}{s}$$

$$V_o = f \frac{C_s}{C_I} \int V_s dt$$

$$= 10^6 \frac{1}{5} \int 1 dt$$



(c) finite gain

Initial charge on C_s capacitor

$$Q_i = C_s V_s = 1 \text{ pC}$$

discharge C_s into C_I

$$\frac{V_o}{V_i} = -1000$$

final charge on $C_s = -V_i C_s$ final charge on $C_I = (V_o - V_i) C_I$

charge conservation

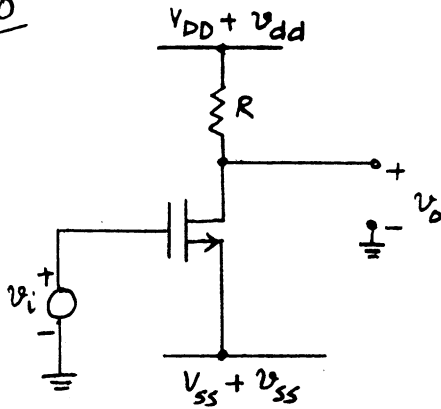
$$(V_o - V_i) C_I - V_i C_s = C_s (1 \text{ V})$$

$$V_o + \frac{V_o}{1000} + \frac{V_o}{1000} (0.2) = 0.2$$

$$V_o = \frac{0.2 \text{ V}}{1 + \frac{1.2}{1000}} \text{ per step}$$

↑
error term

6.10



$$\frac{v_o}{v_i} = -g_m (R \parallel r_o)$$

$$\frac{v_o}{v_{dd}} = \frac{r_o}{R + r_o}$$

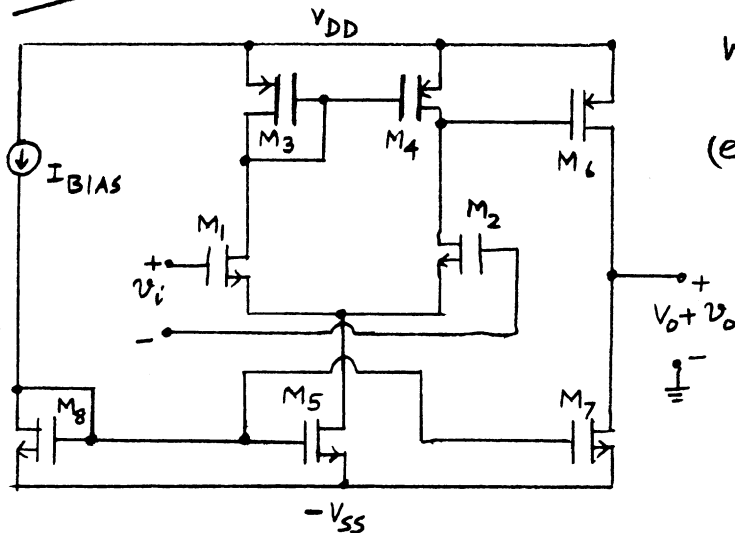
$$\text{From (6.51), } \text{PSRR}^+ = \frac{\frac{r_o}{R + r_o}}{-g_m \frac{R r_o}{R + r_o}} = \frac{-1}{g_m R}$$

$$\frac{v_o}{v_{ss}} = \left(g_m + \frac{1}{r_o} \right) (R \parallel r_o)$$

$$\text{From (6.51), } \text{PSRR}^- = \frac{\left(g_m + \frac{1}{r_o} \right) (R \parallel r_o)}{-g_m (R \parallel r_o)}$$

$$\text{PSRR}^- = - \left(1 + \frac{1}{g_m r_o} \right)$$

6.11



$$(a) A_v = \frac{v_o}{v_i} = -g_{m1} (r_{o2} \parallel r_{o4}) g_{m6} (r_{o6} \parallel r_{o7})$$

same as (6.56)

$$A_v = -\frac{2}{V_{ov1}} \frac{2}{|V_{ov6}|} \left(\frac{V_{A2} |V_{A4}|}{V_{A2} + |V_{A4}|} \right) \left(\frac{|V_{A6}| V_{A7}}{|V_{A6}| + V_{A7}} \right)$$

(b) output swing

$$V_{ov7} - V_{SS} \leq V_o \leq V_{DD} - |V_{ov6}|$$

(c) If (6.66) is satisfied,

$$\begin{aligned} V_o &= V_{DD} - V_{SD6} \\ &= V_{DD} - V_{S63} \\ &= V_{DD} + V_{t3} + V_{ov3} \end{aligned}$$

Note $V_{ov3} < 0$,Also $V_{t3} < 0$ for enhancement mode

$$V_{os}(\text{sys}) = \frac{V_{DD} + V_{t3} + V_{ov3} - \frac{V_{DD} - V_{SS}}{2}}{A_v}$$

(d) CMRR

From (6.71),

$$\text{CMRR} \approx (2 g_{m1} r_{\text{tail}}) g_{m3} (r_{o2} \parallel r_{o4})$$

Where $r_{\text{tail}} = r_{o5}$

(e) CM Input range

To keep M_5 in active region,

$$V_{IC} > V_{ov3} + V_{t1} + V_{ov1} - V_{SS}$$

To keep M_1 in active region,

$$V_{GD1} < V_{t1}$$

$$V_{IC} - (V_{DD} + V_{t3} + V_{ov3}) < V_{t1}$$

$$V_{IC} < V_{DD} + V_{t3} + V_{t1} + V_{ov3}$$

Note $V_{ov3} < 0$

Also $V_{t3} < 0$ for enhancement mode. So, the CM input range is,

$$V_{ov5} + V_{t1} + V_{ov1} - V_{SS} < V_{IC} \\ < V_{DD} + V_{t3} + V_{t1} + V_{ov3}$$

(f) From an argument similar to that leading to (6.86), $A^- \approx 0$.

So, $PSRR^- \rightarrow \infty$ for low frequencies with perfect matching.

Also,

$$A^+ = \frac{v_o}{v_{dd}} = \frac{r_{o7}}{r_{o6} + r_{o7}} = \frac{V_{A7}}{|V_{A6}| + V_{A7}}$$

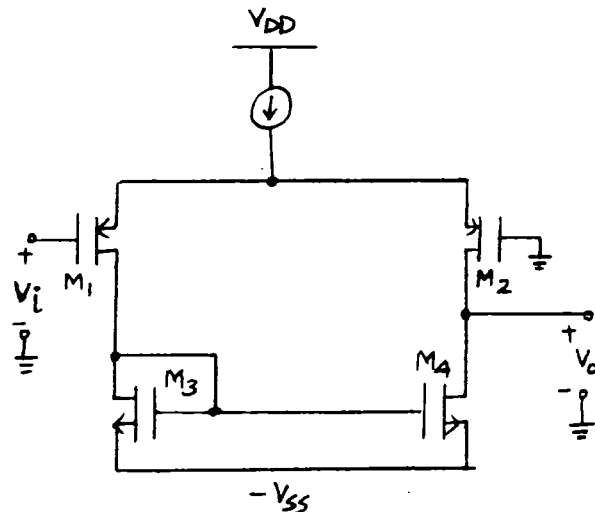
$$\text{Then } PSRR^+ = \frac{A_{dm}}{A^+}$$

$$= \frac{\frac{-2}{V_{ov1}} \frac{2}{|V_{ov6}|} \left(\frac{V_{A2} |V_{A4}|}{V_{A2} + |V_{A4}|} \right) \left(\frac{|V_{A6}| V_{A7}}{|V_{A6}| + V_{A7}} \right)}{\frac{V_{A7}}{|V_{A6}| + V_{A7}}}$$

$$= \frac{-2}{V_{ov1}} \frac{2}{|V_{ov6}|} \left(\frac{V_{A2} |V_{A4}|}{V_{A2} + |V_{A4}|} \right) |V_{A6}|$$

6.12

(a) For simplicity, replace M_5 in Fig (6.16) with an ideal current source. Although this change makes the common mode gain of the op amp zero, this change does not affect the characteristics of the circuit for differential mode inputs



In the circuit above, the gate of M_2 is grounded and the input is applied to only the gate of M_1 . The resulting differential-mode input is the same as in Fig 6.16. The common mode input above may differ from that in Fig 6.16. In fact the common mode input in Fig 6.16 is not specified. However, the effect of a common mode input in Fig 6.16 is small as long as M_5 operates as a current source.

Also, a common-mode input in the drawing above has no effect on the output as long as all the transistors operate in the active region.

The first term in (6.69) predicts that if the only mismatch is $V_{t1} > V_{t2}$, $V_{os} > 0$. Assume at first $V_{t1} = V_{t2}$. Then allow V_{t1} to increase while $V_i = 0$. Since M_1 is a p-channel device, increasing V_{t1} increases I_{D3} , which decreases V_o .

Since the gain from V_i to V_o is positive, V_i must be increased to increase V_o so that $V_{DS4} = V_{DS3}$. Therefore, $V_{os} > 0$ in this case.

The second term in (6.69) predicts that if $V_{t3} > V_{t4}$, $V_{os} > 0$. Assume at first $V_{t3} = V_{t4}$. Then allow V_{t3} to increase while $V_i = 0$. Since $V_{GS4} = V_{GS3} = V_{t3} + V_{ov3}$, increasing V_{t3} increases V_{GS4} , which decreases V_o . Since the gain from V_i to V_o is positive, V_i must be increased to increase V_o so that $V_{DS4} = V_{DS3}$. Therefore, $V_{os} > 0$ in this case.

The third term in (6.69) predicts that if $(\frac{W}{L})_3 > (\frac{W}{L})_4$, $V_{os} < 0$ because $V_{ov(L2)} < 0$

for p-channel input devices.

Assume at first that

$(\frac{W}{L})_3 = (\frac{W}{L})_4$. Then allow $(\frac{W}{L})_3$ to increase while $V_i = 0$. This change decreases V_{ov3} , which in turn decreases V_{GS4} because $V_{GS4} = V_{GS3} = V_{t3} + V_{ov3}$. As a result, V_o increases when $(\frac{W}{L})_3$ increases, and V_i must be decreased to decrease V_o .

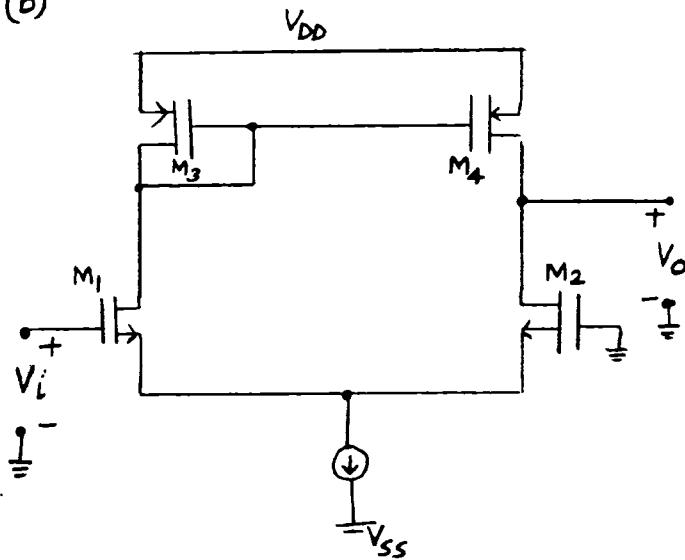
Therefore, $V_{os} < 0$ in this case.

The last term in (6.69) predicts that if $(\frac{W}{L})_1 > (\frac{W}{L})_2$, $V_{os} > 0$ because $V_{ov(L-2)} < 0$ for p-channel input devices.

Assume at first that

$(\frac{W}{L})_1 = (\frac{W}{L})_2$. Then allow $(\frac{W}{L})_1$ to increase while $V_i = 0$. This change increases I_{D3} and decreases V_o . As a result, V_i must be increased to increase V_o . Therefore $V_{os} > 0$ in this case.

(b)



I_{D2} because the tail current is constant. As a result V_o increases. Therefore, V_i must be decreased to decrease V_o and $V_{os} < 0$ in this case.

In practice, the polarity of the mismatches is not usually known. The main value of this problem is in developing a physical insight about the

behaviour of a differential pair with a current mirror load.

First term : Increasing V_{t1} while

$V_i = 0$ decreases I_{D1} , which decreases V_o . So V_i must be increased to increase V_o and force $V_{DS3} = V_{DS4}$. Therefore, $V_{os} > 0$ in this case.

Second term : Increasing V_{t3} while $V_i = 0$

decreases V_{SG4} because $V_{SG4} = V_{SG3} = -V_{t3} - V_{OV3}$. So, this change decreases V_o . Therefore, V_i must be increased to increase V_o , and $V_{os} > 0$ in this case.

Third term : Increasing $(W/L)_3$ while

$V_i = 0$ decreases $|V_{OV3}|$, decreasing V_{SG4} and V_o . Therefore, V_i must be increased to increase V_o , and $V_{os} > 0$ in this case.

Last term : Increasing $(W/L)_1$ while

$V_i = 0$ increases I_{D1} , in turn decreasing

6.13 From (6.69),

$$V_{os} = \Delta V_{t(3-4)} \frac{g_{m3}}{g_{m1}}$$

From (1.180) with $\left(\frac{W}{L}\right)_3 = \left(\frac{W}{L}\right)_1$

and $|I_{D1}| = |I_{D3}|$,

$$\frac{g_{m3}}{g_{m1}} = \sqrt{\frac{\mu_3}{\mu_1}}$$

μ_3 = mobility of M_3

μ_1 = mobility of M_1

$$(a) V_{os} = \Delta V_{t(3-4)} \sqrt{\frac{450}{150}} = 10 \text{ mV}(\sqrt{3}) \\ = 17.3 \text{ mV}$$

$$(b) V_{os} = \Delta V_{t(3-4)} \sqrt{\frac{150}{450}} = 10 \text{ mV}\left(\frac{1}{\sqrt{3}}\right) \\ = 5.8 \text{ mV}$$

(c) The offset is smaller in (b) because the mobility of p-channel transistors is less than that of n-channel transistors.

6.14

With an n-channel input pair

(1) The input-referred offset voltage resulting from the mismatch between the thresholds of m_3 and m_4 is reduced.

(2) V_{DD} can be included in the common mode input range using only enhancement mode transistors

(3) $PSRR^-$ is improved.

(4) The W/L of the input transistors needed to obtain a given transconductance is reduced. As a result, the input capacitance is reduced.

(5) The input-referred thermal noise voltage is reduced (see chapter 11)

6.15

$$200 \mu A = |I_{D_8}| = |I_{D_5}| = |I_{D_7}| = I_{D_6}$$

$$100 \mu A = I_{D_1} = I_{D_2} = I_{D_3} = I_{D_4}$$

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{3.9 (8.85 \times 10^{-14} \text{ F/cm})}{80 \text{ \AA}}$$

$$= 431 \text{ nF/cm}^2$$

$$\mu_n C_{ox} = \frac{450 \text{ cm}^2}{\text{V}\cdot\text{s}} \cdot 431 \frac{\text{nF}}{\text{cm}^2}$$

$$= 194 \mu A/V^2$$

$$k'_n = 194 \mu A/V^2$$

$$k'_p = 64.7 \mu A/V^2$$

$$\frac{v_o}{v_i} = -g_{m_2} (r_{o2} \parallel r_{o4}) g_{m_6} (r_{o6} \parallel r_{o7})$$

$$\frac{1}{r_{o2}} = \frac{I_{D_2}}{L_{eff}} \frac{dX_d}{dV_{DS}} = \frac{100 \mu A}{0.72 \mu m} (0.04 \mu) = 5.56 \mu$$

$$r_{o2} = 180 \text{ k}\Omega = r_{o4}$$

$$r_{o6} = 90 \text{ k}\Omega = r_{o7}$$

$$L_{eff} = L - X_d - 2L_d$$

$$= 1 - 0.1 - 2(0.09)$$

$$= 0.72 \mu m$$

$$g_{m_2} = \sqrt{2 k'_p \frac{W}{L_{eff}} I_{D_2}}$$

$$= \sqrt{2 (64.7 \mu) \left(\frac{150}{0.72} \right) (100 \mu)}$$

$$= 1640 \mu A/V$$

$$g_{m_6} = \sqrt{2 (194 \mu) \left(\frac{100}{0.72} \right) (200 \mu)}$$

$$= 3280 \mu A/V$$

$$\frac{v_o}{v_i} = -(1.64 \text{ m}) (90 \text{ k}) (3.28 \text{ m}) (45 \text{ k})$$

$$= -2.18 \times 10^4$$

common mode range:

From (6.75),

$$V_{IC} > V_{t1} + V_{t3} + V_{OV3} - V_{SS}$$

$$V_{OV3} = \sqrt{\frac{2(100)}{194 (50/0.72)}} = 0.12 \text{ V}$$

$$V_{IC} > -0.8 + 0.6 + 0.12 - 1.5$$

$$V_{IC} > -1.58 \text{ V}$$

From (6.77),

$$V_{IC} < V_{t1} + V_{OV1} + V_{OV5} + V_{DD}$$

$$V_{OV5} = -\sqrt{\frac{2(200)}{64.7 (150/0.72)}} = -0.17 \text{ V}$$

$$V_{OV1} = -\sqrt{\frac{2(100)}{64.7 (150/0.72)}} = -0.12 \text{ V}$$

$$V_{IC} < -0.8 - 0.12 - 0.17 + 1.5$$

$$V_{IC} < 0.41 \text{ V}$$

From (6.86),

$$\frac{v_o}{v_{dd}} \cong 0$$

From (6.87),

$$\frac{v_o}{v_{ss}} = \frac{r_{o7}}{r_{o6} + r_{o7}} = 0.5$$

TWO-STAGE CMOS AMPLIFIER

VDD 100 0 1.5

VSS 200 0 -1.5

M1 7 5 4 4 PMOS W=150U L=1U

M2 8 6 4 4 PMOS W=150U L=1U

M3 7 7 200 200 NMOS W=50U L=1U

M4 8 7 200 200 NMOS W=50U L=1U

M5 4 3 100 100 PMOS W=150U L=1U

M6 9 8 200 200 NMOS W=100U L=1U

M7 9 3 100 100 PMOS W=150U L=1U

M8 3 3 100 100 PMOS W=150U L=1U

IBIAS 3 200 200U

* THE DC OFFSET IS ADJUSTED BY TRIAL AND ERROR

* TO SET THE OUTPUT TO ZERO.

V11 5 2 4.6U

V12 6 2 0

VIC 2 0 0

*LEFF = LDRAMM - 2LD -XD = 1 - 2(0.09) - 0.1 = 0.72 UM

*LAMEDA=(DID/DVDS)/LEFF = 0.04U/0.72U = 0.0555

.MODEL NMOS NMOS LEVEL=1 KP=194U VTO=0.6 LAMEDA=0.0555

.MODEL PMOS PMOS LEVEL=1 KP=64.7U VTO=-0.8 LAMEDA=0.0555

.OPTIONS NOPAGE NOMOD

.WIDTH OUT=80

.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U

.OP

.TF V(9) V11

.END

**** OPERATING POINT INFORMATION TRON= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:2	= 0.	0:3	= 5.024E-01	0:4	= 9.357E-01
+0:5	= 4.600E-06	0:6	= 0.	0:7	= -7.609E-01
+0:8	= -7.602E-01	0:9	= 3.026E-04	0:100	= 1.500E+00
+0:200	= -1.500E+00				

SUBCKT

ELEMENT	0:M1	0:M2	0:M3	0:M4
MODEL	0:PMOS	0:PMOS	0:NMOS	0:NMOS
ID	-9.772E-05	-9.772E-05	9.772E-05	9.772E-05
IBS	0.	0.	0.	0.
IBD	1.697E-14	1.696E-14	-7.391E-15	-7.398E-15
VGS	-9.357E-01	-9.357E-01	7.391E-01	7.391E-01
VDS	-1.696E+00	-1.695E+00	7.391E-01	7.398E-01
VBS	0.	0.	0.	0.
VTH	-8.000E-01	-8.000E-01	6.000E-01	6.000E-01
VDSAT	-1.357E-01	-1.357E-01	1.391E-01	1.391E-01
BETA	1.062E-02	1.062E-02	1.010E-02	1.010E-02
GAM EFF	0.	0.	0.	0.
GM	1.441E-03	1.441E-03	1.405E-03	1.405E-03
GDS	4.957E-06	4.957E-06	5.210E-06	5.210E-06
GMB	0.	0.	0.	0.

SUBCKT

ELEMENT	0:M5	0:M6	0:M7	0:M8
MODEL	0:PMOS	0:NMOS	0:PMOS	0:PMOS
ID	-1.954E-04	2.053E-04	-2.053E-04	-2.000E-04
IBS	0.	0.	0.	0.
IBD	5.643E-15	-1.500E-14	1.500E-14	9.976E-15
VGS	-9.976E-01	7.398E-01	-9.976E-01	-9.976E-01
VDS	-5.643E-01	1.500E+00	-1.499E+00	-9.976E-01
VBS	0.	0.	0.	0.
VTH	-8.000E-01	6.000E-01	-8.000E-01	-8.000E-01
VDSAT	-1.976E-01	1.398E-01	-1.976E-01	-1.976E-01
BETA	1.001E-02	2.102E-02	1.051E-02	1.024E-02
GAM EFF	0.	0.	0.	0.
GM	1.978E-03	2.937E-03	2.078E-03	2.024E-03
GDS	1.052E-05	1.052E-05	1.052E-05	1.052E-05
GMB	0.	0.	0.	0.

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(9)/V11 = -1.975E+04
 INPUT RESISTANCE AT V11 = 1.000E+20
 OUTPUT RESISTANCE AT V(9) = 4.754E+04

TWO-STAGE CMOS AMPLIFIER (MAXIMUM COMMON-MODE INPUT VOLTAGE)

VDD 100 0 1.5

VSS 200 0 -1.5

M1 7 5 4 4 PMOS W=150U L=1U

M2 8 6 4 4 PMOS W=150U L=1U

M3 7 7 200 200 NMOS W=50U L=1U

M4 8 7 200 200 NMOS W=50U L=1U

M5 4 3 100 100 PMOS W=150U L=1U

M6 9 8 200 200 NMOS W=100U L=1U

M7 9 3 100 100 PMOS W=150U L=1U

M8 3 3 100 100 PMOS W=150U L=1U

IBIAS 3 200 200U

* THE DC OFFSET IS ADJUSTED BY TRIAL AND ERROR

* TO SET THE OUTPUT TO ZERO.

V11 5 2 13.7U

V12 6 2 0

* THE MAXIMUM VALUE OF VIC IS ADJUSTED BY TRIAL AND ERROR

* UNTIL M5 BARELY OPERATES IN THE ACTIVE REGION

* (WHERE |VDS| > |VDSAT| FOR M5)

VIC 2 0 0.36

*LEFF = LDRAMM - 2LD -XD = 1 - 2(0.09) - 0.1 = 0.72 UM

*LAMEDA=(DID/DVDS)/LEFF = 0.04U/0.72U = 0.0555

.MODEL NMOS NMOS LEVEL=1 KP=194U VTO=0.6 LAMEDA=0.0555

.MODEL PMOS PMOS LEVEL=1 KP=64.7U VTO=-0.8 LAMEDA=0.0555

.OPTIONS NOPAGE NOMOD

.WIDTH OUT=80

.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U

.OP

.TF V(9) V11

.END

**** OPERATING POINT INFORMATION TRON= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:2	= 3.600E-01	0:3	= 5.024E-01	0:4	= 1.293E+00
+0:5	= 3.600E-01	0:6	= 3.600E-01	0:7	= -7.622E-01
+0:8	= -7.602E-01	0:9	= 1.329E-04	0:100	= 1.500E+00
+0:200	= -1.500E+00				

**** MOSFETS

SUBCKT

ELEMENT	0:M1	0:M2	0:M3	0:M4
MODEL	0:PMOS	0:PMOS	0:NMOS	0:NMOS
ID	-9.584E-05	-9.585E-05	9.584E-05	9.585E-05
IBS	0.	0.	0.	0.
IBD	2.055E-14	2.053E-14	-7.378E-15	-7.398E-15
VGS	-9.331E-01	-9.332E-01	7.378E-01	7.378E-01
VDS	-2.055E+00	-2.053E+00	7.378E-01	7.398E-01
VBS	0.	0.	0.	0.
VTH	-8.000E-01	-8.000E-01	6.000E-01	6.000E-01
VDSAT	-1.331E-01	-1.332E-01	1.378E-01	1.378E-01
BETA	1.081E-02	1.081E-02	1.010E-02	1.010E-02
GAM EFF	0.	0.	0.	0.
GM	1.440E-03	1.440E-03	1.391E-03	1.391E-03
GDS	4.774E-06	4.775E-06	5.110E-06	5.110E-06
GMB	0.	0.	0.	0.

SUBCKT

ELEMENT	0:M5	0:M6	0:M7	0:M8
MODEL	0:PMOS	0:NMOS	0:PMOS	0:PMOS
ID	-1.917E-04	2.053E-04	-2.053E-04	-2.000E-04
IBS	0.	0.	0.	0.
IBD	2.068E-15	-1.500E-14	1.500E-14	9.976E-15
VGS	-9.976E-01	7.398E-01	-9.976E-01	-9.976E-01
VDS	-2.068E-01	1.500E+00	-1.499E+00	-9.976E-01
VBS	0.	0.	0.	0.
VTH	-8.000E-01	6.000E-01	-8.000E-01	-8.000E-01
VDSAT	-1.976E-01	1.398E-01	-1.976E-01	-1.976E-01
BETA	9.816E-03	2.102E-02	1.051E-02	1.024E-02
GAM EFF	0.	0.	0.	0.
GM	1.940E-03	2.937E-03	2.078E-03	2.024E-03
GDS	1.052E-05	1.052E-05	1.052E-05	1.052E-05
GMB	0.	0.	0.	0.

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(9)/V11 = -2.029E+04
 INPUT RESISTANCE AT V11 = 1.000E+20
 OUTPUT RESISTANCE AT V(9) = 4.753E+04

TWO-STAGE CMOS AMPLIFIER (MINIMUM COMMON-MODE INPUT VOLTAGE)

```

VDD 100 0 1.5
VSS 200 0 -1.5
M1 7 5 4 4 PMOS W=150U L=1U
M2 8 6 4 4 PMOS W=150U L=1U
M3 7 7 200 200 NMOS W=50U L=1U
M4 8 7 200 200 NMOS W=50U L=1U
M5 4 3 100 100 PMOS W=150U L=1U
M6 9 8 200 200 NMOS W=100U L=1U
M7 9 3 100 100 PMOS W=150U L=1U
M8 3 3 100 100 PMOS W=150U L=1U
IBIAS 3 200 200U
* THE DC OFFSET IS ADJUSTED BY TRIAL AND ERROR
* TO SET THE OUTPUT TO ZERO.
V11 5 2 -39.7U
V12 6 2 0
* THE MINIMUM VALUE OF VIC IS ADJUSTED BY TRIAL AND ERROR
* UNTIL M1 BARELY OPERATES IN THE ACTIVE REGION
* (WHERE |VDS| > |VDSAT| FOR M1)
VIC 2 0 -1.55
*LEFF = LDRAMN - 2LD -XD = 1 - 2(0.09) - 0.1 = 0.72 UM
*LAMBDA=(DSD/DVDS)/LEFF = 0.04U/0.72U = 0.0555
.MODEL NMOS NMOS LEVEL=1 KP=194U VTO=0.6 LAMBDA=0.0555
.MODEL PMOS PMOS LEVEL=1 KP=64.7U VTO=-0.8 LAMBDA=0.0555
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.OP
.TF V(9) V11
.END

```

```

**** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000
      NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:2      =-1.550E+00 0:3      = 5.024E-01 0:4      =-6.030E-01
+0:5      =-1.550E+00 0:6      =-1.550E+00 0:7      =-7.552E-01
+0:8      =-7.602E-01 0:9      = 6.068E-04 0:100     = 1.500E+00
+0:200     =-1.500E+00

```

**** MOSFETS

SUBCKT

```

ELEMENT 0:M1 0:M2 0:M3 0:M4
MODEL 0:PMOS 0:PMOS 0:NMOS 0:NMOS
ID -1.058E-04 -1.058E-04 1.058E-04 1.058E-04
IBS 0. 0. 0. 0.
IBD 1.523E-15 1.572E-15 -7.448E-15 -7.398E-15
VGS -9.471E-01 -9.470E-01 7.448E-01 7.448E-01
VDS -1.523E-01 -1.572E-01 7.448E-01 7.398E-01
VBS 0. 0. 0. 0.
VTH -8.000E-01 -8.000E-01 6.000E-01 6.000E-01
VDSAT -1.471E-01 -1.470E-01 1.448E-01 1.448E-01
BETA 9.787E-03 9.790E-03 1.010E-02 1.010E-02
GAM KFF 0. 0. 0. 0.
GM 1.439E-03 1.439E-03 1.462E-03 1.462E-03
GDS 5.824E-06 5.821E-06 5.640E-06 5.640E-06
GMB 0. 0. 0. 0.

```

SUBCKT

```

ELEMENT 0:M5 0:M6 0:M7 0:M8
MODEL 0:PMOS 0:NMOS 0:PMOS 0:PMOS
ID -2.116E-04 2.053E-04 -2.053E-04 -2.000E-04
IBS 0. 0. 0. 0.
IBD 2.103E-14 -1.501E-14 1.499E-14 9.976E-15
VGS -9.976E-01 7.398E-01 -9.976E-01 -9.976E-01
VDS -2.103E+00 1.500E+00 -1.499E+00 -9.976E-01
VBS 0. 0. 0. 0.
VTH -8.000E-01 6.000E-01 -8.000E-01 -8.000E-01
VDSAT -1.976E-01 1.398E-01 -1.976E-01 -1.976E-01
BETA 1.084E-02 2.102E-02 1.051E-02 1.024E-02
GAM KFF 0. 0. 0. 0.
GM 2.142E-03 2.937E-03 2.077E-03 2.024E-03
GDS 1.052E-05 1.052E-05 1.052E-05 1.052E-05
GMB 0. 0. 0. 0.

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(9)/V11 = -1.750E+04
INPUT RESISTANCE AT V11 = 1.000E+20
OUTPUT RESISTANCE AT V(9) = 4.754E+04

```

TWO-STAGE CMOS AMPLIFIER (GAIN FROM VDD)

```

VDD 100 0 1.5
VSS 200 0 -1.5
M1 7 5 4 4 PMOS W=150U L=1U
M2 8 6 4 4 PMOS W=150U L=1U
M3 7 7 200 200 NMOS W=50U L=1U
M4 8 7 200 200 NMOS W=50U L=1U
M5 4 3 100 100 PMOS W=150U L=1U
M6 9 8 200 200 NMOS W=100U L=1U
M7 9 3 100 100 PMOS W=150U L=1U
M8 3 3 100 100 PMOS W=150U L=1U
IBIAS 3 200 200U
* THE DC OFFSET IS ADJUSTED BY TRIAL AND ERROR
* TO SET THE OUTPUT TO ZERO.
V11 5 2 4.6U
V12 6 2 0
VIC 2 0 0
*LEFF = LDRAMN - 2LD -XD = 1 - 2(0.09) - 0.1 = 0.72 UM
*LAMBDA=(DSD/DVDS)/LEFF = 0.04U/0.72U = 0.0555
.MODEL NMOS NMOS LEVEL=1 KP=194U VTO=0.6 LAMBDA=0.0555
.MODEL PMOS PMOS LEVEL=1 KP=64.7U VTO=-0.8 LAMBDA=0.0555
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.OP
.TF V(9) VDD
.END
**** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000
      NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:2      = 0. 0:3      = 5.024E-01 0:4      = 9.357E-01
+0:5      = 4.600E-06 0:6      = 0. 0:7      =-7.609E-01
+0:8      =-7.602E-01 0:9      = 3.026E-04 0:100     = 1.500E+00
+0:200     =-1.500E+00
**** SMALL-SIGNAL TRANSFER CHARACTERISTICS
V(9)/VDD = -1.647E-02
INPUT RESISTANCE AT VDD = 4.723E+04
OUTPUT RESISTANCE AT V(9) = 4.754E+04

```

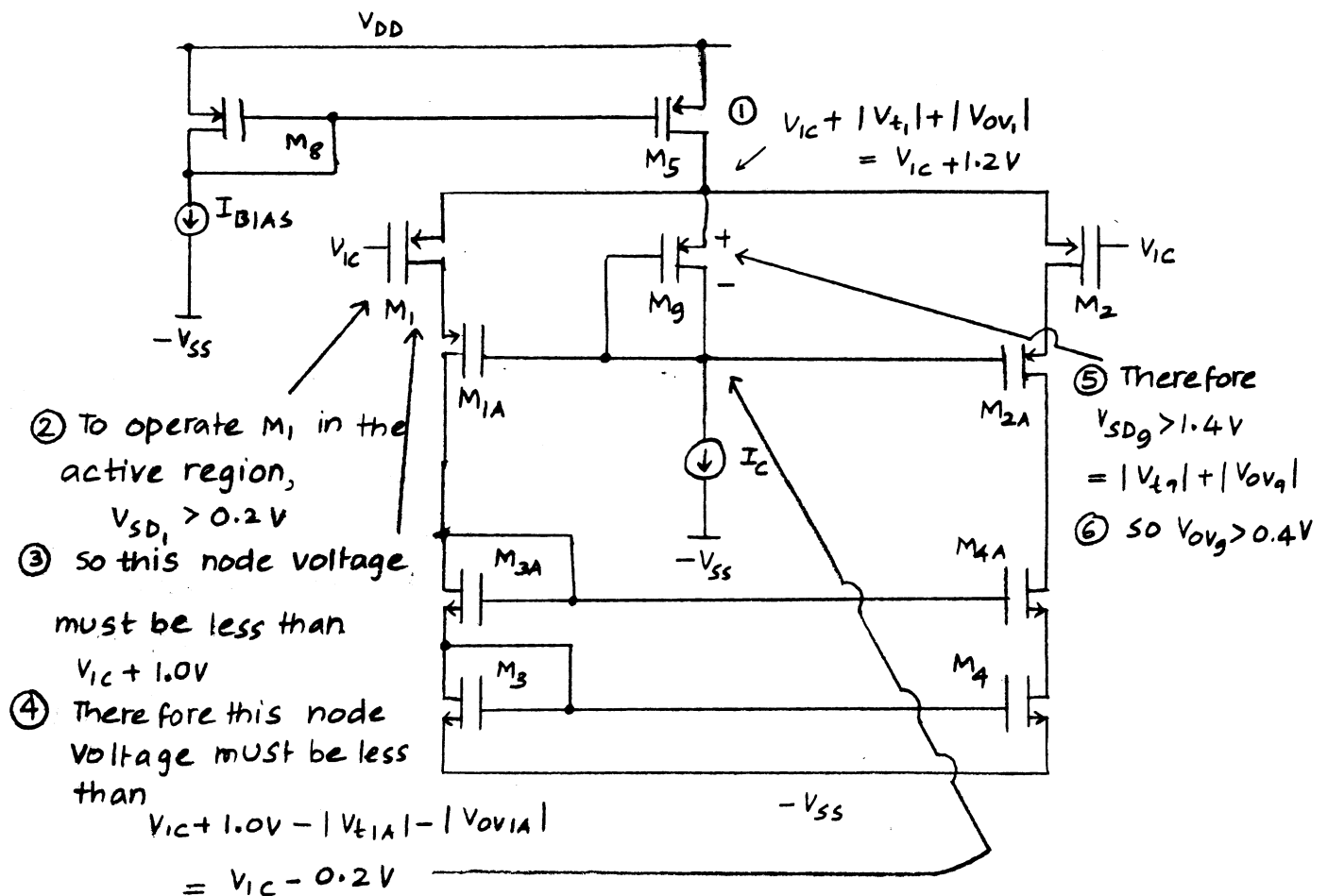
TWO-STAGE CMOS AMPLIFIER (GAIN FROM VSS)

```

VDD 100 0 1.5
VSS 200 0 -1.5
M1 7 5 4 4 PMOS W=150U L=1U
M2 8 6 4 4 PMOS W=150U L=1U
M3 7 7 200 200 NMOS W=50U L=1U
M4 8 7 200 200 NMOS W=50U L=1U
M5 4 3 100 100 PMOS W=150U L=1U
M6 9 8 200 200 NMOS W=100U L=1U
M7 9 3 100 100 PMOS W=150U L=1U
M8 3 3 100 100 PMOS W=150U L=1U
IBIAS 3 200 200U
* THE DC OFFSET IS ADJUSTED BY TRIAL AND ERROR
* TO SET THE OUTPUT TO ZERO.
V11 5 2 4.6U
V12 6 2 0
VIC 2 0 0
*LEFF = LDRAMN - 2LD -XD = 1 - 2(0.09) - 0.1 = 0.72 UM
*LAMBDA=(DSD/DVDS)/LEFF = 0.04U/0.72U = 0.0555
.MODEL NMOS NMOS LEVEL=1 KP=194U VTO=0.6 LAMBDA=0.0555
.MODEL PMOS PMOS LEVEL=1 KP=64.7U VTO=-0.8 LAMBDA=0.0555
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.OP
.TF V(9) VSS
.END
**** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000
      NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:2      = 0. 0:3      = 5.024E-01 0:4      = 9.357E-01
+0:5      = 4.600E-06 0:6      = 0. 0:7      =-7.609E-01
+0:8      =-7.602E-01 0:9      = 3.026E-04 0:100     = 1.500E+00
+0:200     =-1.500E+00
**** SMALL-SIGNAL TRANSFER CHARACTERISTICS
V(9)/VSS = 5.063E-01
INPUT RESISTANCE AT VSS = 1.865E+05
OUTPUT RESISTANCE AT V(9) = 4.754E+04

```

6.16



→ For all transistors except m_9 , $|V_t| = 1V$ and $|V_{ov}| = 0.2V$

→ To operate M_5 in the active region,

$$V_{IC} < V_{DD} - |V_{t1}| - |V_{ov1}| - |V_{ov5}|$$

$$V_{IC} < V_{DD} - 1.4 \text{ V}$$

→ To operate M_{1A} in the active region, $V_{SD(1A)} > |V_{OV1A}| = 0.2V$

$$V_S(1A) = V_{IC} + 1V$$

$$V_D(1A) = -V_{SS} + V_{t3} + V_{OV3} + V_{t3A} + V_{OV3A}$$

$$= -V_{SS} + 2.4V$$

$$V_{SD(1A)} = V_{IC} + 1V - (-V_{SS} + 2.4V) > 0.2V$$

$$V_{IC} - 1.4 + V_{SS} > 0.2V$$

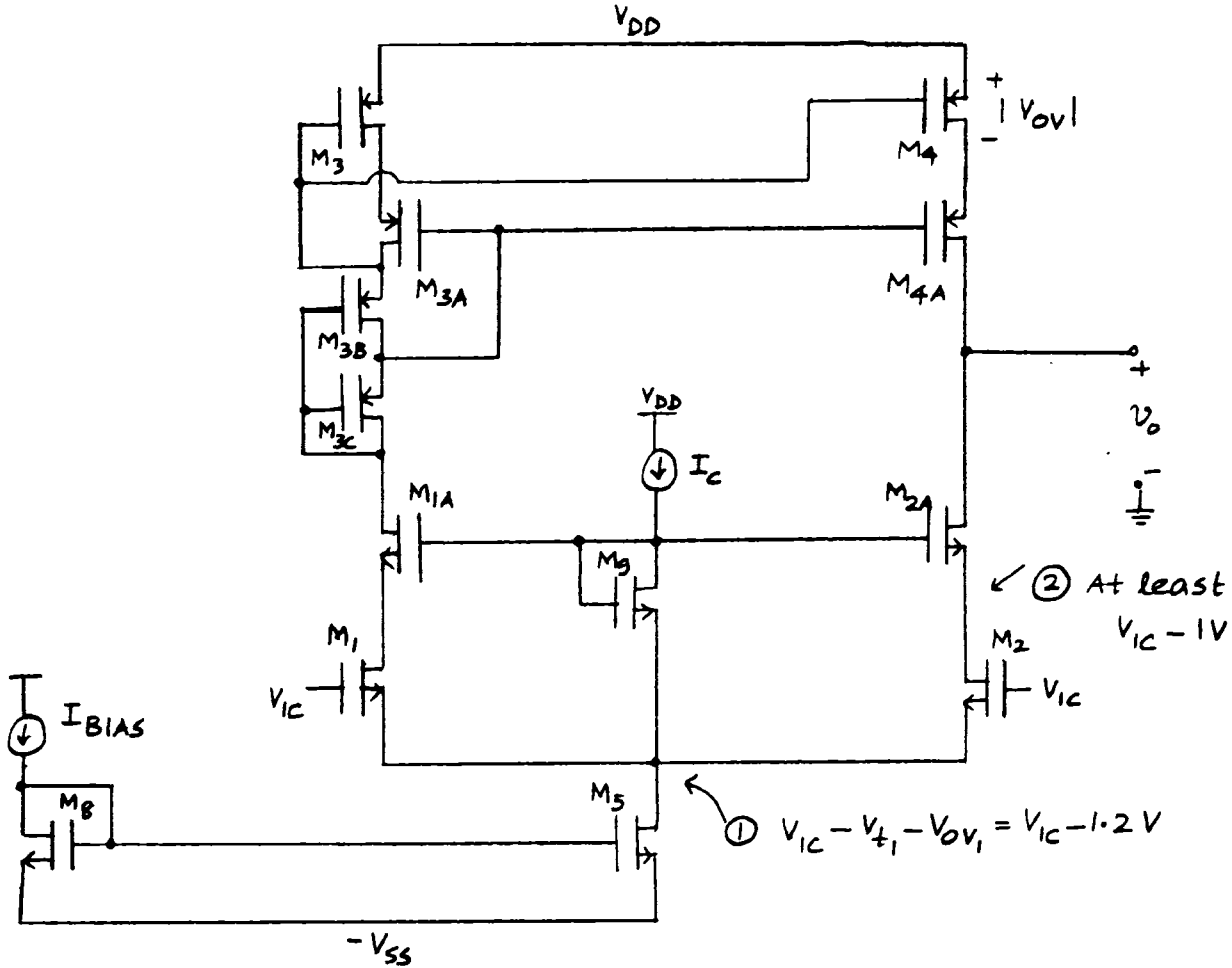
$$V_{IC} > -V_{SS} + 1.6V$$

To simultaneously satisfy both constraints on V_{IC} , the minimum supply difference

$$= V_{DD} - (-V_{SS}) = V_{DD} + V_{SS} = 3V$$

This value can be reduced with smaller threshold and overdrive magnitudes.

6.17 Using a sooch-cascode current mirror,



Maximum swing :

$$V_O < V_{DD} - |V_{OV_4}| - |V_{OV_{4A}}| = V_{DD} - 0.4 \text{ V}$$

Minimum swing :

$$V_o > V_{IC} - 1V + V_{OV_{2A}} = V_{IC} - 0.8V$$

To keep M_5 in the active region,

$$V_{IC} > -V_{SS} + V_{t_1} + V_{OV_1} + V_{OV_5} = -V_{SS} + 1.4V$$

Minimum swing:

$$V_o > V_{IC} - 0.8 > -V_{SS} + 1.4 - 0.8 = -V_{SS} + 0.6V$$

For example, if $V_{DD} = V_{SS} = 1.5 \text{ V}$

$$-0.9 \text{ V} < V_D < 1.1 \text{ V}$$

6.18

To operate M_5 in the active region,

$$V_{IC} < V_{DD} + V_{t1} + V_{OV1} + V_{OV5}$$

$$V_{IC} < V_{DD} - 1V - 0.2V - 0.2V$$

$$V_{IC} < V_{DD} - 1.4V$$

To operate M_1 in the active region,

$$V_{GD1} > V_{t1}$$

so a channel does not exist at the drain of M_1 ,

$$V_{GD1} > V_{t1}$$

$$V_{G1} = V_{IC}$$

$$V_{D1} = -V_{SS} + V_{OV11}$$

$$V_{IC} - (-V_{SS} + V_{OV11}) > V_{t1}$$

$$V_{IC} > -V_{SS} + V_{OV11} + V_{t1}$$

$$V_{IC} > -V_{SS} + 0.2V - 1V$$

$$V_{IC} > -V_{SS} - 0.8V$$

6.19

In the bias circuit,

$$v_{gs(102)} = 0 \text{ because } I_{BIAS} = \text{constant}$$

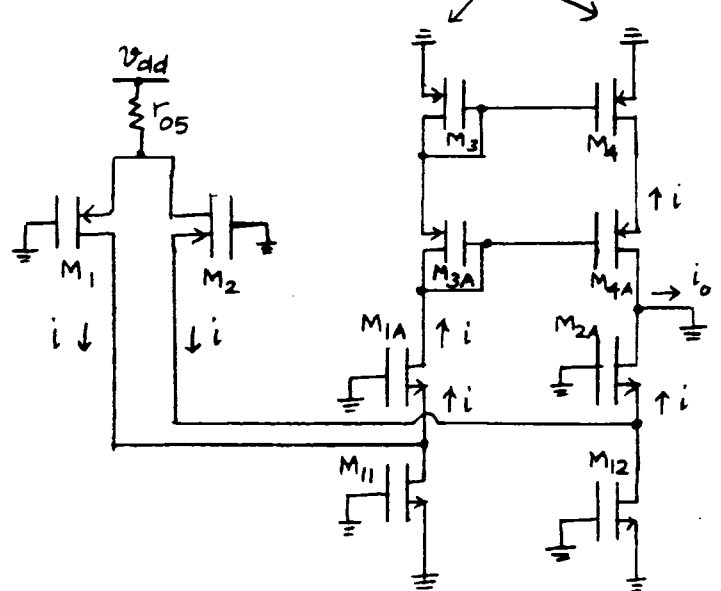
In other words, $v_{gs(102)} = V_{GS(102)} = \text{constant}$. Therefore, v_{dd}

Variations also appear on V_{BIAS} ,

As a result, $v_{gs(5)} = 0$

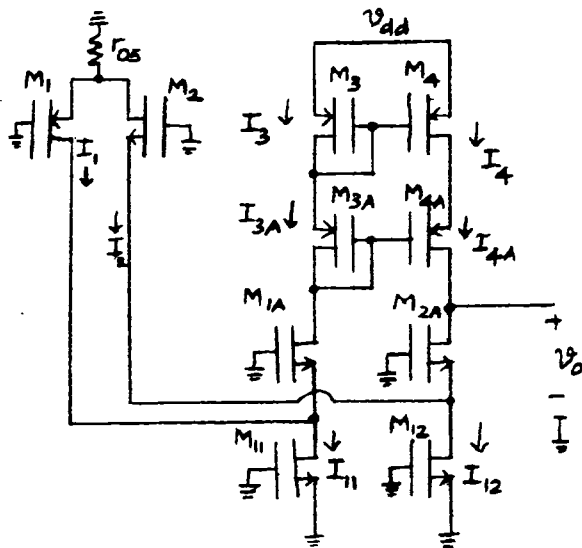
consider v_{dd} variations through M_5 with $v_{gs(5)} = 0$. m_5 can be modeled simply as r_{o5} in the following small signal model

At first, ignore v_{dd} variations here



Here, the v_{dd} variation appears as a common-mode input to the differential pair, causing a common mode change in the drain currents of m_1 and m_2 (i). Since the drain currents of m_{11} and m_{12} are constant, the source currents of m_{1A} and m_{2A} are i (as labeled). Since the gate current of M_{1A} is zero, the small-signal current in the drain of M_{1A} is also i . This small-signal current is mirrored to the drain of M_{4A} by the cascode current mirror. Therefore, $i_o = i - i = 0$

So, the gain from v_{dd} to the output is zero here. Now, consider v_{dd} variations on the sources of M_3 and M_4



$I_3 = I_{3A} \approx \text{constant}$ because M_1 and M_{11} act as current sources. So, $v_{gs(3)} = v_{gs(3A)} = 0$

Since $v_{gs(4)} = v_{gs(3)}$, $v_{gs(4)} = 0$

Since $v_{ds(3)} = v_{ds(4)}$, $v_{gs(4A)} = v_{gs(3A)} = 0$

$I_{4A} = I_{3A}$ because $I_{11} = I_2$

and $I_1 = I_2$

Therefore, $v_{ds(4A)} = v_{ds(3A)} = v_{gs(3A)} = 0$
and v_{dd} variations appear at the output $\frac{v_o}{v_{dd}} = 1$

In the bias circuit,

$I_{D(108)} \approx \text{constant}$ because

$I_{BIAS} = \text{constant}$ and because

$M_{101}, M_{102}, M_{108}$ and M_{109} form a cascode current mirror

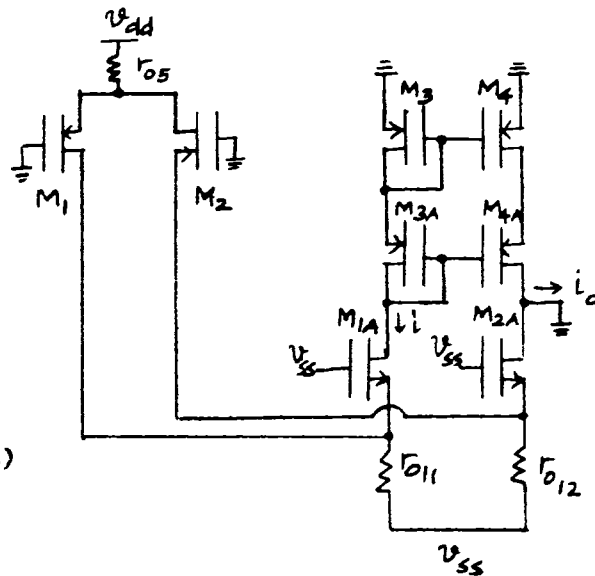
Therefore, $v_{gs(107)} \approx 0$

Similarly, $v_{gs(106)} \approx 0$

Therefore, variations in $-V_{ss}$ also appear on V_{BIAS2} and V_{BIAS3} .

Since $v_{gs(11)} = v_{gs(12)} = v_{gs(107)} \approx 0$,

M_{11} and M_{12} can be modeled simply as r_{o11} and r_{o12} .



v_{ss} variations cause equal or common-mode variations in the drain currents of M_{1A} and M_{2A} , which cancel at the output because of the cascode current mirror

Therefore $\frac{v_o}{v_{ss}} = 0$

FOLDED-CASCODE MOS OP AMP

```

VDD 100 0 2.5
VSS 200 0 -2.5
M1 1 10 8 8 CMOSF W=200U L=1U
M2 2 0 8 8 CMOSF W=200U L=1U
M1A 5 12 1 200 CMOSN W=100U L=1U
M2A 6 12 2 200 CMOSN W=100U L=1U
M3 3 3 100 100 CMOSF W=200U L=1U
M4 4 3 100 100 CMOSF W=200U L=1U
M3A 5 5 3 100 CMOSF W=200U L=1U
M4A 6 5 4 100 CMOSF W=200U L=1U
M5 8 11 100 100 CMOSF W=200U L=1U
M11 1 13 200 200 CMOSN W=100U L=1U
M12 2 13 200 200 CMOSN W=100U L=1U
M101 101 101 11 100 CMOSF W=200U L=1U
M102 11 11 100 100 CMOSF W=200U L=1U
M103 103 11 100 100 CMOSF W=200U L=1U
M104 12 101 103 100 CMOSF W=200U L=1U
M105 12 12 106 200 CMOSN W=100U L=1U
M106 106 12 200 200 CMOSN W=20U L=1U
M107 13 13 200 200 CMOSN W=100U L=1U
M108 13 101 109 100 CMOSF W=200U L=1U
M109 109 11 100 100 CMOSF W=200U L=1U
IB 101 200 100U
VI 10 0 0 AC 1
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=100M VTO=0.7 KP=200U
.MODEL CMOSF PMOS LEVEL=1 LAMBDA=100M VTO=-0.7 KP=100U
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.TF V(6) VI
.END

```

**** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE
+0:1	= -2.312E+00 0:2	= -2.312E+00 0:3	= 1.739E+00		
+0:4	= 1.739E+00 0:5	= 9.779E-01 0:6	= 9.779E-01		
+0:10	= 0. 0:11	= 1.703E+00 0:12	= -1.557E+00		
+0:13	= -1.703E+00 0:100	= 2.500E+00 0:101	= 9.075E-01		
+0:103	= 1.694E+00 0:106	= -2.354E+00 0:109	= 1.694E+00		
+0:200	= -2.500E+00 0:8	= 7.645E-01			

**** MOSFETS

```

SUBCKT
ELEMENT 0:M1 0:M2 0:M1A 0:M2A 0:M3
MODEL 0:CMOSF 0:CMOSF 0:CMOSN 0:CMOSN 0:CMOSF
ID -5.435E-05 -5.435E-05 4.009E-05 4.009E-05 -4.009E-05
IBS 0. 0. -1.871E-15 -1.871E-15 0.
IBD -3.077E-14 3.077E-14 -3.478E-14 -3.478E-14 7.610E-15
VGS -7.645E-01 -7.645E-01 7.549E-01 7.549E-01 -7.610E-01
VDS -3.077E+00 -3.077E+00 3.290E+00 3.290E+00 -7.610E-01
VBS 0. 0. -1.871E-01 -1.871E-01 0.
VTH -7.000E-01 -7.000E-01 7.000E-01 7.000E-01 -7.000E-01
VDSAT -6.447E-02 -6.447E-02 5.492E-02 5.492E-02 -6.104E-02
BETA 2.615E-02 2.615E-02 2.658E-02 2.658E-02 2.152E-02
GAM EFF 0. 0. 0. 0. 0.
GM 1.686E-03 1.686E-03 1.460E-03 1.460E-03 1.314E-03
GDS 4.156E-06 4.156E-06 3.017E-06 3.017E-06 3.726E-06
GMB 0. 0. 0. 0. 0.

```

```

SUBCKT
ELEMENT 0:M4 0:M3A 0:M4A 0:M5 0:M11
MODEL 0:CMOSF 0:CMOSF 0:CMOSN 0:CMOSF 0:CMOSN
ID -4.009E-05 -4.009E-05 -4.009E-05 -1.087E-04 9.444E-05
IBS 0. 7.610E-15 7.610E-15 0. 0.
IBD 7.610E-15 1.522E-14 1.522E-14 1.736E-14 -1.871E-15
VGS -7.610E-01 -7.610E-01 -7.610E-01 -7.962E-01 7.963E-01
VDS -7.610E-01 -7.610E-01 -7.610E-01 -1.735E+00 1.871E-01
VBS 0. 7.610E-01 7.610E-01 0. 0.
VTH -7.000E-01 -7.000E-01 -7.000E-01 -7.000E-01 7.000E-01
VDSAT -6.104E-02 -6.104E-02 -6.104E-02 -9.624E-02 9.629E-02
BETA 2.152E-02 2.152E-02 2.152E-02 2.347E-02 2.037E-02
GAM EFF 0. 0. 0. 0. 0.
GM 1.314E-03 1.314E-03 1.314E-03 2.259E-03 1.962E-03
GDS 3.726E-06 3.726E-06 3.726E-06 9.262E-06 9.271E-06
GMB 0. 0. 0. 0. 0.

```

SUBCKT

```

ELEMENT 0:M12 0:M101 0:M102 0:M103 0:M104
MODEL 0:CMOSN 0:CMOSF 0:CMOSF 0:CMOSF 0:CMOSF
ID 9.444E-05 -1.000E-04 -1.000E-04 -1.001E-04 -1.001E-04
IBS 0. 7.962E-15 0. 0. 8.056E-15
IBD -1.871E-15 1.592E-14 7.962E-15 8.056E-15 4.058E-14
VGS 7.963E-01 -7.962E-01 -7.962E-01 -7.962E-01 -7.869E-01
VDS 1.871E-01 -7.962E-01 -7.962E-01 -8.056E-01 -3.252E+00
VBS 0. 7.962E-01 0. 0. 8.056E-01
VTH 7.000E-01 -7.000E-01 -7.000E-01 -7.000E-01 -7.000E-01
VDSAT 9.629E-02 -9.624E-02 -9.624E-02 -9.624E-02 -8.690E-02
BETA 2.037E-02 2.159E-02 2.159E-02 2.161E-02 2.650E-02
GAM EFF 0. 0. 0. 0. 0.
GM 1.962E-03 2.078E-03 2.078E-03 2.080E-03 2.303E-03
GDS 9.271E-06 9.262E-06 9.262E-06 9.262E-06 7.552E-06
GMB 0. 0. 0. 0. 0.

```

SUBCKT

```

ELEMENT 0:M105 0:M106 0:M107 0:M108 0:M109
MODEL 0:CMOSN 0:CMOSN 0:CMOSN 0:CMOSF 0:CMOSF
ID 1.001E-04 1.001E-04 1.001E-04 -1.001E-04 -1.001E-04
IBS -1.458E-15 0. 0. 8.060E-15 0.
IBD -9.421E-15 -1.458E-15 -7.963E-15 4.204E-14 8.060E-15
VGS 7.963E-01 9.421E-01 7.963E-01 -7.864E-01 -7.962E-01
VDS 7.963E-01 1.458E-01 7.963E-01 -3.397E+00 -8.060E-01
VBS -1.458E-01 0. 0. 8.060E-01 0.
VTH 7.000E-01 7.000E-01 7.000E-01 -7.000E-01 -7.000E-01
VDSAT 9.628E-02 1.458E-01 9.629E-02 -8.643E-02 -9.624E-02
BETA 2.159E-02 4.058E-03 2.159E-02 2.680E-02 2.161E-02
GAM EFF 0. 0. 0. 0. 0.
GM 2.079E-03 5.916E-04 2.079E-03 2.316E-03 2.080E-03
GDS 9.270E-06 4.006E-04 9.271E-06 7.471E-06 9.262E-06
GMB 0. 0. 0. 0. 0.

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(6)/VI	= 4.403E+04
INPUT RESISTANCE AT VI	= 1.000E+20
OUTPUT RESISTANCE AT V(6)	= 2.635E+07

FOLDED-CASCODE MOS OP AMP (GAIN FROM VDD)

```

VDD 100 0 2.5 AC 1
VSS 200 0 -2.5
M1 1 0 8 8 CMOSF W=200U L=1U
M2 2 0 8 8 CMOSF W=200U L=1U
M1A 5 12 1 200 CMOSN W=100U L=1U
M2A 6 12 2 200 CMOSN W=100U L=1U
M3 3 3 100 100 CMOSF W=200U L=1U
M4 4 3 100 100 CMOSF W=200U L=1U
M3A 5 5 3 100 CMOSF W=200U L=1U
M4A 6 5 4 100 CMOSF W=200U L=1U
M5 8 11 100 100 CMOSF W=200U L=1U
M11 1 13 200 200 CMOSN W=100U L=1U
M12 2 13 200 200 CMOSN W=100U L=1U
M101 101 101 11 100 CMOSF W=200U L=1U
M102 11 11 100 100 CMOSF W=200U L=1U
M103 103 11 100 100 CMOSF W=200U L=1U
M104 12 101 103 100 CMOSF W=200U L=1U
M105 12 12 106 200 CMOSN W=100U L=1U
M106 106 12 200 200 CMOSN W=20U L=1U
M107 13 13 200 200 CMOSN W=100U L=1U
M108 13 101 109 100 CMOSF W=200U L=1U
M109 109 11 100 100 CMOSF W=200U L=1U
IB 101 200 100U
VI 10 0 0 AC 1
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=100M VTO=0.7 KP=200U
.MODEL CMOSF PMOS LEVEL=1 LAMBDA=100M VTO=-0.7 KP=100U
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.TF V(6) VDD
.END

```

```

**** OPERATING POINT INFORMATION      THOM= 27.000 TEMP= 27.000
  NODE   =VOLTAGE      NODE   =VOLTAGE      NODE   =VOLTAGE
+0:1     =-2.312E+00 0:2     =-2.312E+00 0:3     = 1.739E+00
+0:4     = 1.739E+00 0:5     = 9.779E-01 0:6     = 9.779E-01
+0:10    = 0.         0:11    = 1.703E+00 0:12    =-1.557E+00
+0:13    =-1.703E+00 0:100    = 2.500E+00 0:101    = 9.075E-01
+0:103   = 1.694E+00 0:106    =-2.354E+00 0:109    = 1.694E+00
+0:200   =-2.500E+00 0:8      = 7.645E-01
**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

```

V(6)/VDD      = 1.006E+00
INPUT RESISTANCE AT VDD      = 4.710E+06
OUTPUT RESISTANCE AT V(6)    = 2.635E+07

```

FOLDED-CASCODE MOS OF AMP (GAIN FROM VSS)

```

*****
VDD 100 0 2.5
VSS 200 0 -2.5 AC 1
M1 1 0 8 8 CMOSF W=200U L=1U
M2 2 0 8 8 CMOSF W=200U L=1U
M1A 5 12 1 200 CMOSN W=100U L=1U
M2A 6 12 2 200 CMOSN W=100U L=1U
M3 3 3 100 100 CMOSF W=200U L=1U
M4 4 3 100 100 CMOSF W=200U L=1U
M3A 5 5 3 100 CMOSF W=200U L=1U
M4A 6 5 4 100 CMOSF W=200U L=1U
M5 8 11 100 100 CMOSF W=200U L=1U
M11 1 13 200 200 CMOSN W=100U L=1U
M12 2 13 200 200 CMOSN W=100U L=1U
M101 101 101 11 100 CMOSF W=200U L=1U
M102 11 11 100 100 CMOSF W=200U L=1U
M103 103 11 100 100 CMOSF W=200U L=1U
M104 12 101 103 100 CMOSF W=200U L=1U
M105 12 12 106 200 CMOSN W=100U L=1U
M106 106 12 200 200 CMOSN W=200U L=1U
M107 13 13 200 200 CMOSN W=100U L=1U
M108 13 101 109 100 CMOSF W=200U L=1U
M109 109 11 100 100 CMOSF W=200U L=1U
IB 101 200 100U
VI 10 0 0 AC 1
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=100M VTO=0.7 KP=200U
.MODEL CMOSF PMOS LEVEL=1 LAMBDA=100M VTO=-0.7 KP=100U
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.TF V(6) VSS
.END

```

```

**** OPERATING POINT INFORMATION      THOM= 27.000 TEMP= 27.000
  NODE   =VOLTAGE      NODE   =VOLTAGE      NODE   =VOLTAGE
+0:1     =-2.312E+00 0:2     =-2.312E+00 0:3     = 1.739E+00
+0:4     = 1.739E+00 0:5     = 9.779E-01 0:6     = 9.779E-01
+0:10    = 0.         0:11    = 1.703E+00 0:12    =-1.557E+00
+0:13    =-1.703E+00 0:100    = 2.500E+00 0:101    = 9.075E-01
+0:103   = 1.694E+00 0:106    =-2.354E+00 0:109    = 1.694E+00
+0:200   =-2.500E+00 0:8      = 7.645E-01
**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

```

V(6)/VSS      = 5.429E-05
INPUT RESISTANCE AT VSS      = 6.493E+06
OUTPUT RESISTANCE AT V(6)    = 2.635E+07

```

6.20

For $I_{O(max)} = \pm 100 \mu A$,

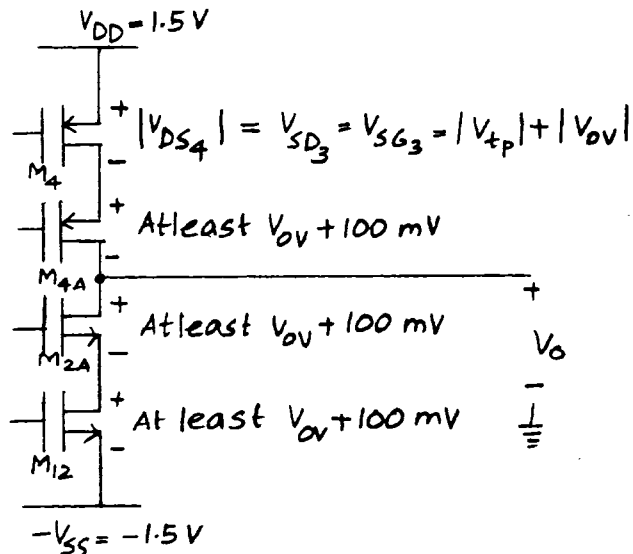
$$I_{D11} = I_{D12} = 100 \mu A$$

Then half of I_{D11} should come from M_1 and the other half from M_{1A}

$$\text{so, } |I_{D1}| = |I_{D2}| = |I_{D1A}| = I_{D2A} = 50 \mu A$$

$$\text{so, } |I_{D3A}| = |I_{D3}| = |I_{D4}| = |I_{D4A}| = 50 \mu A$$

For the output swing requirement, concentrate on the output branch



$$V_{O(p-p)} = V_{DD} - (-V_{SS}) - |V_{tp}| - 4V_{ov} - 300 \text{ mV}$$

Requirement $V_{O(p-p)} > 1.5V$

$$1.5 < 1.5 - (-1.5) - 0.8 - 4V_{ov} - 0.3$$

$$-0.4 < -4V_{ov} \rightarrow V_{ov} < 0.1V$$

$$I = \frac{\mu_n}{2} \frac{W}{L} V_{ov}^2 \Rightarrow \frac{W}{L} = \frac{2I}{\mu_n V_{ov}^2}$$

$$\left(\frac{W}{L}\right)_{12} = \frac{2(100)}{194(0.1)^2} \approx 100$$

$$\left(\frac{W}{L}\right)_{2A} = \frac{2(50)}{194(0.1)^2} \approx 50$$

$$\left(\frac{W}{L}\right)_4 = \left(\frac{W}{L}\right)_{4A} = \frac{2(50)}{64.7(0.1)^2} \approx 150$$

For the common-mode range requirement: To operate M_1 in the active region

$$V_{GD1} > V_{t1} = -0.8 \text{ V}$$

$$V_{G1} = V_{IC}$$

$$V_{D1} = -V_{SS} + V_{OV11} + 0.1 \text{ V}$$

$$V_{IC} > -V_{SS} + V_{OV11} + 0.1 \text{ V} + V_{t1} \\ > 1.5 + 0.1 + 0.1 - 0.8 = -2.1 \text{ V}$$

so, the common mode range includes $-V_{SS} = -1.5 \text{ V}$

To operate M_5 in the active region,

$$V_{IC} < V_{DD} + V_{t1} + V_{OV1} + V_{OV5}$$

$$V_{IC} < 1.5 - 0.8 + 2V_{OV}$$

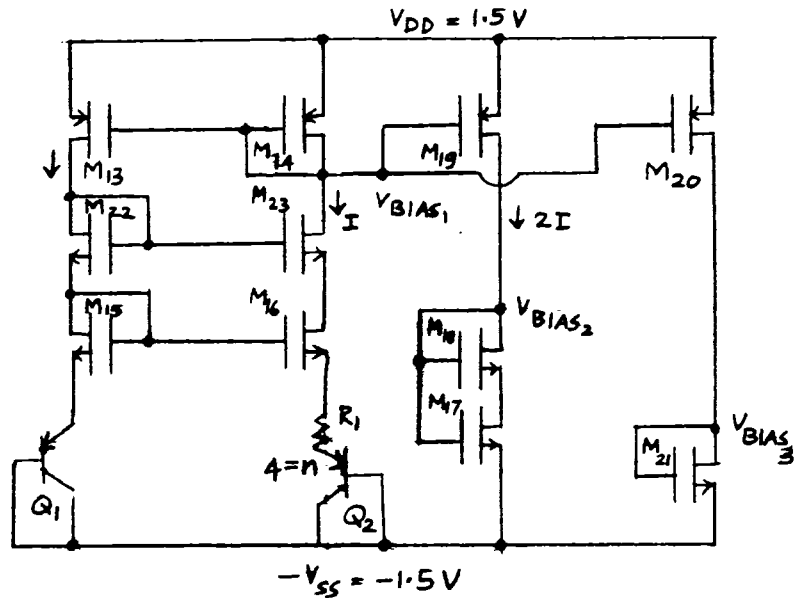
$$0.5 < 0.7 + 2V_{OV}$$

$$V_{OV} = V_{OV1} = V_{OV5} > -0.1 \text{ V}$$

$$\left(\frac{W}{L}\right)_1 = \frac{2(50)}{64.7(0.1)^2} \approx 150$$

$$\left(\frac{W}{L}\right)_5 = \frac{2(100)}{64.7(0.1)^2} \approx 300$$

BIAS CIRCUIT:



$$I = \frac{V_T \ln(n)}{R_1} = 50 \mu\text{A} \Rightarrow$$

$$R_1 = \frac{V_T \ln 4}{50 \mu\text{A}} = 721 \Omega$$

check headroom requirements in the bias circuit. For the branch including M_{13}

$$V_{DD} - (|V_{OV13}| + 0.1 \text{ V}) - V_{t22} - V_{OV22} - V_{t15} - V_{OV15} - 0.7 - (-V_{SS}) = 0$$

$$\text{Let } |V_{OV13}| = V_{OV22} = V_{OV15} = V_{OV}$$

$$V_{t22} = V_{t15} = 0.6 \text{ V}$$

$$1.5 - 0.1 - 0.6 - 0.6 - 0.7 - (-1.5) = 3V_{OV}$$

$$1 = 3V_{OV} \Rightarrow V_{OV} = 0.33 \text{ V}$$

so, this branch operates with all transistors in the active region if $V_{OV} < 0.33 \text{ V}$

For the branch including M_{14} ,

$$V_{DD} - |V_{t14}| - |V_{ov14}| - (V_{ov23} + 0.1V) - (V_{ov16} + 0.1V) - V_T \ln 4 - 0.7V - (-V_{SS}) = 0$$

$$\text{Let } |V_{ov14}| = V_{ov23} = V_{ov16} = V_{ov}$$

$$V_T \ln 4 = 36 \text{ mV (neglect)}; V_{t14} = -0.8V$$

$$1.5 - 0.8 - 0.1 - 0.1 - 0.7 - (-1.5) = 3V_{ov}$$

$$1.3 = 3 V_{ov}$$

$$V_{ov} = 0.43V$$

so, this branch operates with all transistors in the active region if $V_{ov} < 0.43V$

so, this design will use the previously computed value of $V_{ov} = 0.1V$

$$\left(\frac{W}{L}\right)_{13} = \left(\frac{W}{L}\right)_{14} = \frac{2(50)}{64.7(0.1)^2} \simeq 150$$

$$\left(\frac{W}{L}\right)_{22} = \left(\frac{W}{L}\right)_{23} = \left(\frac{W}{L}\right)_{15} = \left(\frac{W}{L}\right)_{16} = \frac{2(50)}{194(0.1)^2} \simeq 50$$

$$\left(\frac{W}{L}\right)_{19} = \left(\frac{W}{L}\right)_{20} = 2\left(\frac{W}{L}\right)_{14} = 300$$

$$\left(\frac{W}{L}\right)_{18} = \left(\frac{W}{L}\right)_{21} = \frac{2(100)}{194(0.1)^2} \simeq 100$$

M_{18} forces M_{17} to operate in the triode region.

$$\text{From (4.73), } \left(\frac{W}{L}\right)_{17} = \frac{1}{3} \left(\frac{W}{L}\right)_{18} \text{ sets } V_{DS17} = V_{ov} = 0.1V$$

To increase V_{DS17} to $V_{ov} + 0.1V = 0.2V$,

$$\text{reduce } \left(\frac{W}{L}\right)_7 \text{ to about } \frac{1}{5} \left(\frac{W}{L}\right)_{18} = 20$$

This choice is confirmed in simulation. It biases M_{11} & M_{12} so that $V_{DS11} = V_{DS12} \simeq 0.2V$

FOLDED CASCODE OP AMP

```

VDD 100 0 1.5
VSS 200 0 -1.5
M1 17 9 8 8 PMOS W=150U L=1U
M2 18 10 8 8 PMOS W=150U L=1U
M1A 15 2 17 200 NMOS W=50U L=1U
M2A 16 2 18 200 NMOS W=50U L=1U
M3 13 13 100 100 PMOS W=150U L=1U
M4 14 13 100 100 PMOS W=150U L=1U
M3A 15 15 13 13 PMOS W=150U L=1U
M4A 16 15 14 14 PMOS W=150U L=1U
M5 8 1 100 100 PMOS W=300U L=1U
M11 17 3 200 200 NMOS W=100U L=1U
M12 18 3 200 200 NMOS W=100U L=1U
M13 20 1 100 100 PMOS W=150U L=1U
M14 1 1 100 100 PMOS W=150U L=1U
M15 4 4 5 200 NMOS W=50U L=1U
M16 21 4 6 200 NMOS W=50U L=1U
M17 12 2 200 200 NMOS W=10U L=1U
M18 2 2 12 200 NMOS W=100U L=1U
M19 2 1 100 100 PMOS W=300U L=1U
M20 3 1 100 100 PMOS W=300U L=1U
M21 3 3 200 200 NMOS W=100U L=1U
M22 20 20 4 200 NMOS W=50U L=1U
M23 1 20 21 200 NMOS W=50U L=1U
Q1 200 200 5 PNP
Q2 200 200 7 PNP 4
R1 6 7 721

```

.MODEL NMOS NMOS LEVEL=1 KP=194U VTO=0.6 LAMBDA=0.024 GAMMA=0.25

.MODEL PMOS PMOS LEVEL=1 KP=64.7U VTO=-0.8 LAMBDA=0.048 GAMMA=0.25

.MODEL PNP PNP BF=50 IS=2E-15

V11 9 0 0

V12 10 0 0

.OPTIONS NOPAGE NOMOD

.WIDTH OUT=80

.OP

.TF V(16) V11

.END

**** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE
+0:1	= 6.016E-01	0:2	= -5.479E-01	0:3	= -7.971E-01
+0:4	= -1.005E-01	0:5	= -8.820E-01	0:6	= -8.823E-01
+0:7	= -9.176E-01	0:8	= 8.950E-01	0:9	= 0.
+0:10	= 0.	0:12	= -1.282E+00	0:13	= 5.960E-01
+0:14	= 5.960E-01	0:15	= -3.081E-01	0:16	= -3.081E-01
+0:17	= -1.285E+00	0:18	= -1.285E+00	0:20	= 7.586E-01
+0:21	= -1.010E-01	0:100	= 1.500E+00	0:200	= -1.500E+00

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT

```

ELEMENT 0:Q1 0:Q2
MODEL 0:PNP 0:PNP
IB -9.542E-07 -9.612E-07
IC -4.771E-05 -4.806E-05
VBE -6.180E-01 -5.824E-01
VCE -6.180E-01 -5.824E-01
VBC 0. 0.
VS 1.500E+00 1.500E+00
POWER 3.008E-05 2.855E-05
BETAD 5.000E+01 5.000E+01
GM 1.845E-03 1.858E-03
RPI 2.710E+04 2.690E+04
RX 0. 0.
RO 1.293E+13 3.233E+12
BETAAC 5.000E+01 5.000E+01

```

**** MOSFETS

SUBCKT

```

ELEMENT 0:M1 0:M2 0:M1A 0:M2A 0:M3
MODEL 0:PMOS 0:PMOS 0:NMOS 0:NMOS 0:PMOS
ID -4.836E-05 -4.836E-05 5.479E-05 5.479E-05 -5.479E-05
IBS 0. 0. -2.150E-15 -2.150E-15 0.
IBD 2.180E-14 2.180E-14 -1.192E-14 -1.192E-14 9.040E-15
VGS -8.950E-01 -8.950E-01 7.371E-01 7.371E-01 -9.040E-01
VDS -2.180E+00 -2.180E+00 9.769E-01 9.769E-01 -9.040E-01
VBS 0. 0. -2.150E-01 -2.150E-01 0.
VTH -8.000E-01 -8.000E-01 6.320E-01 6.320E-01 -8.000E-01
VDSAT -9.498E-02 -9.498E-02 1.051E-01 1.051E-01 -1.040E-01
BETA 1.072E-02 1.072E-02 9.927E-03 9.927E-03 1.013E-02
GAM EFF 2.500E-01 2.500E-01 2.500E-01 2.500E-01 2.500E-01
GM 1.018E-03 1.018E-03 1.043E-03 1.043E-03 1.053E-03
GDS 2.101E-06 2.101E-06 1.285E-06 1.285E-06 2.521E-06
GMB 1.643E-04 1.643E-04 1.444E-04 1.444E-04 1.700E-04

```

SUBCKT

```

ELEMENT 0:M4 0:M3A 0:M4A 0:M5 0:M11
MODEL 0:PMOS 0:PMOS 0:PMOS 0:PMOS 0:NMOS
ID -5.479E-05 -5.479E-05 -5.479E-05 -9.672E-05 1.032E-04
IBS 0. 0. 0. 0. 0.
IBD 9.040E-15 9.040E-15 9.040E-15 6.050E-15 -2.150E-15
VGS -9.040E-01 -9.040E-01 -9.040E-01 -8.984E-01 7.029E-01
VDS -9.040E-01 -9.040E-01 -9.040E-01 -6.050E-01 2.150E-01
VBS 0. 0. 0. 0. 0.
VTH -8.000E-01 -8.000E-01 -8.000E-01 -8.000E-01 6.000E-01
VDSAT -1.040E-01 -1.040E-01 -1.040E-01 -9.841E-02 1.029E-01
BETA 1.013E-02 1.013E-02 1.013E-02 1.997E-02 1.950E-02
GAM EFF 2.500E-01 2.500E-01 2.500E-01 2.500E-01 2.500E-01
GM 1.053E-03 1.053E-03 1.053E-03 1.966E-03 2.006E-03
GDS 2.521E-06 2.521E-06 2.521E-06 4.511E-06 2.463E-06
GMB 1.700E-04 1.700E-04 1.700E-04 3.172E-04 3.237E-04

```

SUBCKT

```

ELEMENT 0:M12 0:M13 0:M14 0:M15 0:M16
MODEL 0:NMOS 0:PMOS 0:PMOS 0:NMOS 0:NMOS
ID 1.032E-04 -4.867E-05 -4.902E-05 4.867E-05 4.902E-05
IBS 0. 0. 0. -6.180E-15 -6.177E-15
IBD -2.150E-15 7.414E-15 8.984E-15 -1.400E-14 -1.399E-14
VGS 7.029E-01 -8.984E-01 -8.984E-01 7.815E-01 7.818E-01
VDS 2.150E-01 -7.414E-01 -8.984E-01 7.815E-01 7.813E-01
VBS 0. 0. 0. -6.180E-01 -6.177E-01
VTH 6.000E-01 -8.000E-01 -8.000E-01 6.823E-01 6.822E-01
VDSAT 1.029E-01 -9.841E-02 -9.841E-02 9.925E-02 9.961E-02
BETA 1.950E-02 1.005E-02 1.012E-02 9.882E-03 9.882E-03
GAM EFF 2.500E-01 2.500E-01 2.500E-01 2.500E-01 2.500E-01
GM 2.006E-03 9.891E-04 9.963E-04 9.807E-04 9.843E-04
GDS 2.463E-06 2.256E-06 2.256E-06 1.146E-06 1.155E-06
GMB 3.237E-04 1.596E-04 1.608E-04 1.111E-04 1.115E-04

```

SUBCKT

```

ELEMENT 0:M17 0:M18 0:M19 0:M20 0:M21
MODEL 0:NMOS 0:NMOS 0:PMOS 0:PMOS 0:NMOS
ID 1.032E-04 1.032E-04 -1.032E-04 -1.044E-04 1.044E-04
IBS 0. -2.175E-15 0. 0. 0.
IBD -2.175E-15 -9.521E-15 2.048E-14 2.297E-14 -7.029E-15
VGS 9.521E-01 7.347E-01 -8.984E-01 -8.984E-01 7.029E-01
VDS 2.175E-01 7.347E-01 -2.047E+00 -2.297E+00 7.029E-01
VBS 0. -2.175E-01 0. 0. 0.
VTH 6.000E-01 6.324E-01 -8.000E-01 -8.000E-01 6.000E-01
VDSAT 2.175E-01 1.023E-01 -9.841E-02 -9.841E-02 1.029E-01
BETA 1.950E-03 1.974E-02 2.132E-02 2.155E-02 1.973E-02
GAM EFF 2.500E-01 2.500E-01 2.500E-01 2.500E-01 2.500E-01
GM 4.241E-04 2.019E-03 2.098E-03 2.121E-03 2.029E-03
GDS 2.650E-04 2.435E-06 4.511E-06 4.511E-06 2.463E-06
GMB 6.844E-05 2.791E-04 3.385E-04 3.422E-04 3.274E-04

```

SUBCKT

```

ELEMENT 0:M22 0:M23
MODEL 0:NMOS 0:NMOS
ID 4.867E-05 4.902E-05
IBS -1.400E-14 -1.399E-14
IBD -2.259E-14 -2.102E-14
VGS 8.590E-01 8.595E-01
VDS 8.590E-01 7.025E-01
VBS -1.399E+00 -1.399E+00
VTH 7.599E-01 7.598E-01
VDSAT 9.915E-02 9.970E-02
BETA 9.900E-03 9.864E-03
GAM EFF 2.500E-01 2.500E-01
GM 9.816E-04 9.834E-04
GDS 1.144E-06 1.157E-06
GMB 8.677E-05 8.694E-05

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(16)/V11 = 9.290E+04
INPUT RESISTANCE AT V11 = 1.000E+20
OUTPUT RESISTANCE AT V(16) = 9.159E+07

```

FOLDED CASCODE OP AMP (CONNECTED AS VOLTAGE FOLLOWER)

* CONNECT THE OP AMP AS A VOLTAGE FOLLOWER TO SEE THE COMMON-MODE
* INPUT RANGE. THIS CONNECTION ALSO SHOWS THE OUTPUT SWING.

```

VDD 100 0 1.5
VSS 200 0 -1.5
M1 17 9 8 8 PMOS W=150U L=1U
M2 18 16 8 8 PMOS W=150U L=1U
M1A 15 2 17 200 NMOS W=50U L=1U
M2A 16 2 18 200 NMOS W=50U L=1U
M3 13 13 100 100 PMOS W=150U L=1U
M4 14 13 100 100 PMOS W=150U L=1U
M3A 15 15 13 13 PMOS W=150U L=1U
M4A 16 15 14 14 PMOS W=150U L=1U
M5 8 1 100 100 PMOS W=300U L=1U
M11 17 3 200 200 NMOS W=100U L=1U
M12 18 3 200 200 NMOS W=100U L=1U
M13 20 1 100 100 PMOS W=150U L=1U
M14 1 1 100 100 PMOS W=150U L=1U
M15 4 4 5 200 NMOS W=50U L=1U
M16 21 4 6 200 NMOS W=50U L=1U
M17 12 2 200 200 NMOS W=10U L=1U
M18 2 2 12 200 NMOS W=100U L=1U
M19 2 1 100 100 PMOS W=300U L=1U
M20 3 1 100 100 PMOS W=300U L=1U
M21 3 3 200 200 NMOS W=100U L=1U
M22 20 20 4 200 NMOS W=50U L=1U
M23 1 20 21 200 NMOS W=50U L=1U
Q1 200 200 5 PNP
Q2 200 200 7 PNP 4
R1 6 7 721

```

.MODEL NMOS NMOS LEVEL=1 KP=194U VTO=0.6 LAMBDA=0.024 GAMMA=0.25

.MODEL PMOS PMOS LEVEL=1 KP=64.7U VTO=-0.8 LAMBDA=0.048 GAMMA=0.25

.MODEL PNP PNP BF=50 IS=2E-15

V11 9 0 0

V12 10 0 0

.OPTIONS NOPAGE NOMOD

.WIDTH OUT=80

.OP

.TF V(16) V11

.DC V11 -1.7 1.5 0.1

.PLOT DC V(16)

.END

***** DC TRANSFER CURVES THOM= 27.000 TEMP= 27.000

```

VOLT V(16)
(A ) -2.000E+00 -1.000E-00 0. 1.000E+00 2.000E+00
+ + + + +
-1.700E+00 -1.50E+00 -A-----+-----+-----+-----+
-1.600E+00 -1.49E+00 + A + + + + + + + +
-1.500E+00 -1.45E+00 + +A + + + + + + + +
-1.400E+00 -1.39E+00 + +A + + + + + + + +
-1.300E+00 -1.30E+00 + + A + + + + + + + +
-1.200E+00 -1.20E+00 + + A + + + + + + + +
-1.100E+00 -1.10E+00 + + A+ + + + + + + +
-1.000E+00 -1.00E-00 + + A + + + + + + + +
-9.000E-01 -9.00E-01 + + +A + + + + + + + +
-8.000E-01 -8.00E-01 + + + A + + + + + + + +
-7.000E-01 -7.00E-01 + + + A-----+-----+-----+
-6.000E-01 -6.00E-01 + + + A+ + + + + + + +
-5.000E-01 -5.00E-01 + + + A + + + + + + + +
-4.000E-01 -4.00E-01 + + + +A + + + + + + + +
-3.000E-01 -3.00E-01 + + + + A + + + + + + + +
-2.000E-01 -2.00E-01 + + + + A + + + + + + + +
-1.000E-01 -1.00E-01 + + + + A+ + + + + + + +
0. -3.33E-06 + + + + A + + + + + + + +
1.000E-01 1.00E-01 + + + + +A + + + + + + + +
2.000E-01 2.00E-01 + + + + + A + + + + + + + +
3.000E-01 3.00E-01 + + + + + A-----+-----+-----+
4.000E-01 4.00E-01 + + + + + A+ + + + + + + +
5.000E-01 5.00E-01 + + + + + A + + + + + + + +
6.000E-01 6.00E-01 + + + + + +A + + + + + + + +
7.000E-01 6.88E-01 + + + + + + A + + + + + + + +
8.000E-01 6.88E-01 + + + + + + A + + + + + + + +
9.000E-01 6.88E-01 + + + + + + A + + + + + + + +
1.000E+00 6.88E-01 + + + + + + A + + + + + + + +
1.100E+00 6.88E-01 + + + + + + A + + + + + + + +
1.200E+00 6.88E-01 + + + + + + A + + + + + + + +
1.300E+00 6.88E-01 + + + + + + A-----+-----+-----+
1.400E+00 6.88E-01 + + + + + + A + + + + + + + +
1.500E+00 6.88E-01 + + + + + + A + + + + + + + +
+ + + + + + + + + + +

```

**** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:1	= 6.016E-01 0:2	=-5.479E-01 0:3	=-7.971E-01		
+0:4	=-1.005E-01 0:5	=-8.820E-01 0:6	=-8.823E-01		
+0:7	=-9.176E-01 0:8	= 8.950E-01 0:9	= 0.		
+0:10	= 0. 0:12	=-1.282E+00 0:13	= 5.960E-01		
+0:14	= 5.967E-01 0:15	=-3.081E-01 0:16	=-3.327E-06		
+0:17	=-1.285E+00 0:18	=-1.284E+00 0:20	= 7.586E-01		
+0:21	=-1.010E-01 0:100	= 1.500E+00 0:200	=-1.500E+00		

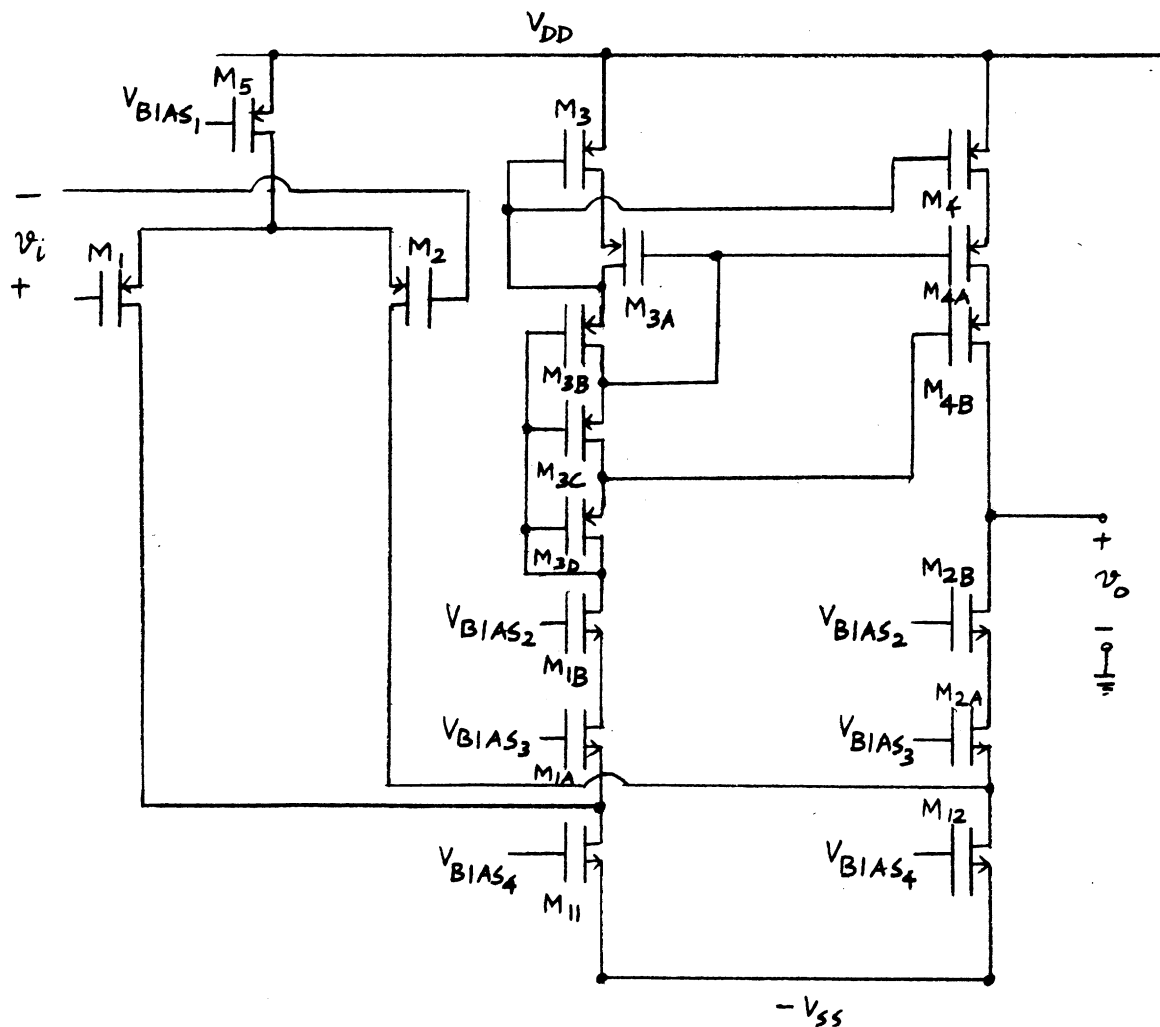
**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(16)/V11 = 1.000E-00
INPUT RESISTANCE AT V11 = 1.000E+20
OUTPUT RESISTANCE AT V(16) = 9.858E+02

```

6.21



From Table (2.4), $\mu_n = 3\mu_p$.
 Therefore, to produce overdrives with equal magnitudes for identical drain current magnitudes, n-channel transistors require $(\frac{W}{L})$ 3 times smaller than corresponding p-channel transistors.

Let $|I_{D1}| = |I_{D2}| = I$

Then $|I_{D5}| = I_{D11} = I_{D12} = 2I$

All other transistors have $|I_D| = I$

For equal overdrive magnitudes,

$$\left(\frac{W}{L}\right)_5 = 2\left(\frac{W}{L}\right)_1$$

$$\left(\frac{W}{L}\right)_{11} = \left(\frac{W}{L}\right)_{12} = \frac{2}{3} \left(\frac{W}{L}\right)_1$$

$$\begin{aligned} \left(\frac{W}{L}\right)_{3D} &= \left(\frac{W}{L}\right)_{3A} = \left(\frac{W}{L}\right)_3 = \left(\frac{W}{L}\right)_4 = \left(\frac{W}{L}\right)_{4A} \\ &= \left(\frac{W}{L}\right)_{4B} = \left(\frac{W}{L}\right)_1 \end{aligned}$$

$M_3, M_{3A}, M_{3B}, M_{3C}, M_{3D}, M_4, M_{4A}$ and M_{4B} form a double-cascode sooth current mirror

From (4.73),

$$\left(\frac{W}{L}\right)_{3c} = \frac{1}{3} \left(\frac{W}{L}\right)_{3D} = \frac{1}{3} \left(\frac{W}{L}\right)_1$$

From Problem (4.8),

$$\left(\frac{W}{L}\right)_{3B} = \frac{1}{5} \left(\frac{W}{L}\right)_{3D} = \frac{1}{5} \left(\frac{W}{L}\right)_1$$

to maximize output swing.

6.22

M_4, M_{4A}, M_{2A} and M_{12} should all operate in the active region for a peak to peak output swing of 2.5V

$$\begin{aligned} V_{DD} - (-V_{SS}) - V_{O(P-P)} &= 1.65 - (-1.65) \\ &= 2.5 \\ &= 0.8V \end{aligned}$$

Divide this amount equally among M_4, M_{4A}, M_{2A} and M_{12} to get $|V_{DS(min)}| = 0.2V$

To set $|V_{DS(min)}| = |V_{OV}| + 0.1V$

choose $|V_{OV}| = 0.1V$

Since all transistors are biased with equal $|V_{OV}|$, set $|V_{OV}| = 0.1V$ for all the transistors

since $I_{BIAS} = 25 \mu A$

assume

$$\begin{aligned} I_{D101} &= I_{D102} = I_{D103} = I_{D104} \\ &= |I_{D105}| = |I_{D106}| = |I_{D107}| = |I_{D108}| \\ &= I_{D109} = I_{D110} \end{aligned}$$

$$\begin{aligned} &= |I_{D111}| = |I_{D112}| \\ &= I_{D113} = I_{D114} = 25 \mu A \end{aligned}$$

$$\text{Since } I_{D25} = |I_{D35}| = 200 \mu A$$

$$I_{D21} = I_{D22} = |I_{D23}| = |I_{D24}| = 100 \mu A$$

$$|I_{D31}| = |I_{D32}| = I_{D33} = I_{D34} = 100 \mu A$$

$$\text{Since } |I_{D5}| = 200 \mu A$$

$$|I_{D1}| = |I_{D2}| = 100 \mu A$$

$$\text{Since } I_{D11} = I_{D12} = 200 \mu A$$

$$\begin{aligned} I_{D1A} &= I_{D2A} \\ &= |I_{D3A}| = |I_{D3}| = |I_{D4}| = I_{D4A} = 100 \mu A \end{aligned}$$

$$\text{Since } |I_D| = \frac{\kappa'}{2} \frac{W}{L} V_{OV}^2$$

$$\frac{W}{L} = \frac{2|I_D|}{\kappa' V_{OV}^2}$$

In the bias circuit,

$$\begin{aligned} \left(\frac{W}{L}\right)_{101} &= \left(\frac{W}{L}\right)_{102} = \left(\frac{W}{L}\right)_{103} = \left(\frac{W}{L}\right)_{104} = \left(\frac{W}{L}\right)_{109} = \left(\frac{W}{L}\right)_{110} = \left(\frac{W}{L}\right)_{113} \\ &= \frac{2(25)}{194(0.1)^2} \approx 25 \end{aligned}$$

In the A_1 amplifiers,

$$\left(\frac{W}{L}\right)_{25} = \frac{2(200)}{194(0.1)^2} \approx 200$$

$$\left(\frac{W}{L}\right)_{21} = \left(\frac{W}{L}\right)_{22} = \frac{2(100)}{194(0.1)^2} \approx 100$$

$$\left(\frac{W}{L}\right)_{23} = \left(\frac{W}{L}\right)_{24} = \frac{2(100)}{64.7(0.1)^2} \approx 300$$

In the A_2 amplifiers,

$$\left(\frac{W}{L}\right)_{35} = \frac{2(200)}{64.7(0.1)^2} \approx 600$$

$$\left(\frac{W}{L}\right)_{31} = \left(\frac{W}{L}\right)_{32} = \frac{2(100)}{64.7(0.1)^2} \approx 300$$

$$\left(\frac{W}{L}\right)_{33} = \left(\frac{W}{L}\right)_{34} = \frac{2(100)}{194(0.1)^2} \approx 100$$

In the main op-amp,

$$\left(\frac{W}{L}\right)_5 = \frac{2(200)}{64.7(0.1)^2} \approx 600$$

$$\left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2 = \frac{2(100)}{64.7(0.1)^2} \approx 300$$

$$\left(\frac{W}{L}\right)_{11} = \left(\frac{W}{L}\right)_{12} = \frac{2(200)}{194(0.1)^2} \approx 200$$

$$\left(\frac{W}{L}\right)_{1A} = \left(\frac{W}{L}\right)_{2A} = \frac{2(100)}{194(0.1)^2} \approx 100$$

$$\left(\frac{W}{L}\right)_{3A} = \left(\frac{W}{L}\right)_3 = \left(\frac{W}{L}\right)_4 = \left(\frac{W}{L}\right)_{4A} = \frac{2(100)}{64.7(0.1)^2} \approx 300$$

From SPICE,

$$\left(\frac{W}{L}\right)_{106} = 5 \text{ to set } |V_{DS106}| \approx 0.1 \text{ V}$$

$$\left(\frac{W}{L}\right)_{114} = 2.5 \text{ to set } V_{DS114} = 0.1 \text{ V}$$

$$\frac{v_o}{v_i} \approx 35 \times 10^6 \text{ with}$$

$$\lambda_n = \frac{0.02}{1-2(0.09)} = 0.024 \text{ V}^{-1}$$

$$|\lambda_p| = \frac{0.04}{1-2(0.09)} = 0.049 \text{ V}^{-1}$$

$$\text{and } |V_{t0}| = 0.7 \text{ V}$$

$$\text{With } V_{ton} = 0.6 \text{ V and } V_{top} = -0.8 \text{ V}$$

$$\frac{v_o}{v_i} = 35 \times 10^4$$

The gain falls in this case because M_{22} in the A_1 amplifiers operates in the triode region. This happens

because $V_{GD_{22}} \approx |V_{tp}| + |V_{ovp}| > V_{t_{22}}$ as explained in section 6.7.

Therefore, increasing $|V_{t0}|$ for p-channel transistors and reducing V_{t0} for n-channel transistors both push M_{22} closer to the triode region.

ACTIVE FOLDED CASCODE OP AMP

VDD 100 0 1.65
VSS 200 0 -1.65

* OP AMP

M1 11 1 5 100 CMOSF W=300U L=1U
M2 12 2 5 100 CMOSF W=300U L=1U
M1A 40 61 11 200 CMOSF W=100U L=1U
M2A 10 62 12 200 CMOSF W=100U L=1U
M3 3 40 100 100 CMOSF W=300U L=1U
M4 4 40 100 100 CMOSF W=300U L=1U
M3A 40 63 3 100 CMOSF W=300U L=1U
M4A 10 64 4 100 CMOSF W=300U L=1U
M5 5 51 100 100 CMOSF W=600U L=1U
M11 11 54 200 200 CMOSF W=200U L=1U
M12 12 54 200 200 CMOSF W=200U L=1U

* AUXILIARY AMPLIFIER SUBCIRCUITS

.SUBCKT AMP1 (21 22 24 26 100 200)

*M1 24 0 21 22 100
M21 23 21 25 200 CMOSF W=100U L=1U
M22 24 22 25 200 CMOSF W=100U L=1U
M23 23 23 100 100 CMOSF W=300U L=1U
M24 24 23 100 100 CMOSF W=300U L=1U
M25 25 26 200 200 CMOSF W=200U L=1U

.ENDS AMP1

.SUBCKT AMP2 (31 32 34 36 100 200)

*M2 34 0 31 32 100
M31 33 31 35 100 CMOSF W=300U L=1U
M32 34 32 35 100 CMOSF W=300U L=1U
M33 33 33 200 200 CMOSF W=100U L=1U
M34 34 33 200 200 CMOSF W=100U L=1U
M35 35 36 100 100 CMOSF W=600U L=1U

.ENDS AMP2

* AUXILIARY AMPLIFIERS

X1 52 3 63 54 100 200 AMP1
X2 52 4 64 54 100 200 AMP1
X3 53 11 61 51 100 200 AMP2
X4 53 12 62 51 100 200 AMP2

* BIAS GENERATOR

IBIAS 100 101 25U
M101 101 101 54 200 CMOSF W=25U L=1U
M102 54 54 200 200 CMOSF W=25U L=1U
M103 103 54 200 200 CMOSF W=25U L=1U
M104 105 101 103 200 CMOSF W=25U L=1U
M105 105 105 52 100 CMOSF W=25U L=1U
M106 52 105 100 100 CMOSF W=5U L=1U
M107 51 51 100 100 CMOSF W=75U L=1U
M108 108 108 51 100 CMOSF W=75U L=1U
M109 108 101 110 200 CMOSF W=25U L=1U
M110 110 54 200 200 CMOSF W=25U L=1U
M111 111 51 100 100 CMOSF W=75U L=1U
M112 113 108 111 100 CMOSF W=75U L=1U
M113 113 113 53 200 CMOSF W=25U L=1U
M114 53 113 200 200 CMOSF W=2.5U L=1U
CL 10 0 4P

.MODEL CMOSF NMOS LEVEL=1

+ TOX=0.8E-08 VTO=0.7 KP=194U LD=0.09U LAMBEA=0.024 GAMMA=0.25

.MODEL CMOSF PMOS LEVEL=1

+ TOX=0.8E-08 VTO=-0.7 KP=64.7U LD=0.09U LAMBEA=0.049 GAMMA=0.25

VIP 1 0 0 AC 1

VIN 2 0 0

.OPTIONS NOPAGE NOMOD

.WIDTH OUT=80

.OP

.TF V(10) VIP

.END

**** MOSFETS

SUBCKT

ELEMENT 0:M1 0:M2 0:M1A 0:M2A 0:M3
MODEL 0:CMOSF 0:CMOSF 0:CMOSF 0:CMOSF 0:CMOSF
ID -9.988E-05 -9.988E-05 9.730E-05 9.730E-05 -9.730E-05
IBS 7.646E-15 7.646E-15 -1.931E-15 -1.931E-15 0.
IBD 3.107E-14 3.107E-14 -2.510E-14 -2.510E-14 2.124E-15
VGS -8.854E-01 -8.854E-01 8.173E-01 8.173E-01 -7.902E-01
VDS -2.342E+00 -2.342E+00 2.316E+00 2.316E+00 -2.124E-01
VBS 7.646E-01 7.646E-01 -1.931E-01 -1.931E-01 0.
VTH -7.984E-01 -7.984E-01 7.290E-01 7.290E-01 -7.000E-01
VDSAT -8.701E-02 -8.701E-02 8.827E-02 8.827E-02 -9.020E-02
BETA 2.639E-02 2.639E-02 2.497E-02 2.497E-02 2.392E-02
GAM EFF 2.500E-01 2.500E-01 2.500E-01 2.500E-01 2.500E-01
GM 2.296E-03 2.296E-03 2.205E-03 2.205E-03 2.157E-03
GDS 4.390E-06 4.390E-06 2.212E-06 2.212E-06 4.719E-06
GMB 2.457E-04 2.457E-04 3.094E-04 3.094E-04 3.482E-04

SUBCKT

ELEMENT 0:M4 0:M3A 0:M4A 0:M5 0:M11
MODEL 0:CMOSF 0:CMOSF 0:CMOSF 0:CMOSF 0:CMOSF
ID -9.730E-05 -9.730E-05 -9.730E-05 -1.998E-04 1.972E-04
IBS 0. 2.124E-15 2.124E-15 0. 0.
IBD 2.124E-15 7.902E-15 7.902E-15 7.646E-15 -1.931E-15
VGS -7.902E-01 -8.211E-01 -8.211E-01 -7.902E-01 7.911E-01
VDS -2.124E-01 -5.778E-01 -5.778E-01 -7.646E-01 1.931E-01
VBS 0. 2.124E-01 2.124E-01 0. 0.
VTH -7.000E-01 -7.317E-01 -7.317E-01 -7.000E-01 7.000E-01
VDSAT -9.020E-02 -8.942E-02 -8.942E-02 -9.019E-02 9.108E-02
BETA 2.392E-02 2.434E-02 2.434E-02 4.912E-02 4.754E-02
GAM EFF 2.500E-01 2.500E-01 2.500E-01 2.500E-01 2.500E-01
GM 2.157E-03 2.176E-03 2.176E-03 4.430E-03 4.330E-03
GDS 4.719E-06 4.637E-06 4.637E-06 9.435E-06 4.711E-06
GMB 3.482E-04 3.018E-04 3.018E-04 7.148E-04 6.987E-04

SUBCKT

ELEMENT 0:M12 0:M101 0:M102 0:M103 0:M104
MODEL 0:CMOSF 0:CMOSF 0:CMOSF 0:CMOSF 0:CMOSF
ID 1.972E-04 2.500E-05 2.500E-05 2.500E-05 2.500E-05
IBS 0. -7.911E-15 0. 0. -7.916E-15
IBD -1.931E-15 -1.683E-14 -7.911E-15 -7.916E-15 -2.199E-14
VGS 7.911E-01 8.922E-01 7.911E-01 7.911E-01 8.917E-01
VDS 1.931E-01 8.922E-01 7.911E-01 7.916E-01 1.407E+00
VBS 0. -7.911E-01 0. 0. -7.916E-01
VTH 7.000E-01 8.012E-01 7.000E-01 7.000E-01 8.013E-01
VDSAT 9.108E-02 9.097E-02 9.108E-02 9.108E-02 9.043E-02
BETA 4.754E-02 6.041E-03 6.027E-03 6.027E-03 6.114E-03
GAM EFF 2.500E-01 2.500E-01 2.500E-01 2.500E-01 2.500E-01
GM 4.330E-03 5.496E-04 5.490E-04 5.490E-04 5.529E-04
GDS 4.711E-06 5.874E-07 5.888E-07 5.888E-07 5.804E-07
GMB 6.987E-04 5.825E-05 5.859E-05 5.859E-05 5.859E-05

SUBCKT

ELEMENT 0:M105 0:M106 0:M107 0:M108 0:M109
MODEL 0:CMOSF 0:CMOSF 0:CMOSF 0:CMOSF 0:CMOSF
ID -2.500E-05 -2.500E-05 -2.500E-05 -2.500E-05 2.500E-05
IBS 2.132E-15 0. 0. 7.902E-15 -7.910E-15
IBD 1.101E-14 2.132E-15 7.902E-15 1.681E-14 -1.619E-14
VGS -8.876E-01 -1.100E+00 -7.902E-01 -8.911E-01 8.922E-01
VDS -8.876E-01 -2.132E-01 -7.902E-01 -8.911E-01 8.277E-01
VBS 2.132E-01 0. 7.902E-01 -7.910E-01 0.
VTH -7.318E-01 -7.000E-01 -7.000E-01 -8.011E-01 8.012E-01
VDSAT -1.559E-01 -2.132E-01 -9.019E-02 -8.998E-02 9.104E-02
BETA 2.058E-03 3.986E-04 6.147E-03 6.176E-03 6.032E-03
GAM EFF 2.500E-01 2.500E-01 2.500E-01 2.500E-01 2.500E-01
GM 3.208E-04 8.497E-05 5.544E-04 5.557E-04 5.492E-04
GDS 1.174E-06 7.601E-05 1.179E-06 1.174E-06 5.883E-07
GMB 4.447E-05 1.371E-05 8.946E-05 5.891E-05 5.821E-05

SUBCKT

ELEMENT 0:M110 0:M111 0:M112 0:M113 0:M114
MODEL 0:CMOSF 0:CMOSF 0:CMOSF 0:CMOSF 0:CMOSF
ID 2.500E-05 -2.500E-05 -2.500E-05 2.500E-05 2.500E-05
IBS 0. 0. 7.913E-15 -1.938E-15 0.
IBD -7.910E-15 7.913E-15 2.286E-14 -1.014E-14 -1.938E-15
VGS 7.911E-01 -7.902E-01 -8.900E-01 8.201E-01 1.014E+00
VDS 7.910E-01 -7.913E-01 -1.494E+00 8.201E-01 1.938E-01
VBS 0. 7.913E-01 -1.938E-01 0. 0.
VTH 7.000E-01 -7.000E-01 -8.012E-01 7.291E-01 7.000E-01
VDSAT 9.108E-02 -9.019E-02 -8.873E-02 9.105E-02 1.938E-01
BETA 6.027E-03 6.147E-03 6.351E-03 6.031E-03 5.942E-04
GAM EFF 2.500E-01 2.500E-01 2.500E-01 2.500E-01 2.500E-01
GM 5.489E-04 5.544E-04 5.635E-04 5.492E-04 1.152E-04
GDS 5.888E-07 1.179E-06 1.141E-06 5.884E-07 7.199E-05
GMB 8.859E-05 8.947E-05 5.972E-05 7.704E-05 1.859E-05

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:1	= 0. 0:2	= 0. 0:3	= 1.437E+00		
+0:4	= 1.437E+00 0:5	= 8.854E-01 0:10	= 8.598E-01		
+0:11	= -1.456E+00 0:12	= -1.456E+00 0:40	= 8.598E-01		
+0:51	= 8.598E-01 0:52	= 1.436E+00 0:53	= -1.456E+00		
+0:54	= -8.589E-01 0:61	= -6.396E-01 0:62	= -6.396E-01		
+0:63	= 6.165E-01 0:64	= 6.165E-01 0:100	= 1.650E+00		
+0:101	= 3.327E-02 0:103	= -8.584E-01 0:105	= 5.492E-01		
+0:108	= -3.128E-02 0:110	= -8.590E-01 0:111	= 8.587E-01		
+0:113	= -6.360E-01 0:200	= -1.650E+00 1:23	= 8.587E-01		
+1:25	= 4.287E-01 2:23	= 8.587E-01 2:25	= 4.287E-01		
+3:33	= -8.563E-01 3:35	= -4.457E-01 4:33	= -8.563E-01		
+4:35	= -4.457E-01				

```

SUBCKT X1 X1 X1 X1 X1
ELEMENT 1:M21 1:M22 1:M23 1:M24 1:M25
MODEL 0:CMOSN 0:CMOSN 0:CMOSP 0:CMOSP 0:CMOSN
ID 1.024E-04 1.036E-04 -1.024E-04 -1.036E-04 2.061E-04
IBS -2.079E-14 -2.079E-14 0. 0. 0.
IBD -2.509E-14 -2.267E-14 7.913E-15 1.033E-14 -2.079E-14
VGS 1.008E+00 1.008E+00 -7.913E-01 -7.913E-01 7.911E-01
VDS 4.300E-01 1.878E-01 -7.913E-01 -1.033E+00 2.078E+00
VBS -2.078E+00 -2.078E+00 0. 0. 0.
VTH 9.155E-01 9.155E-01 -7.000E-01 -7.000E-01 7.000E-01
VDSAT 9.259E-02 9.338E-02 -9.129E-02 -9.129E-02 9.108E-02
BETA 2.390E-02 2.377E-02 2.459E-02 2.487E-02 4.968E-02
GAM EFF 2.500E-01 2.500E-01 2.500E-01 2.500E-01 2.500E-01
GM 2.213E-03 2.219E-03 2.245E-03 2.270E-03 4.525E-03
GDS 2.434E-06 2.476E-06 4.833E-06 4.833E-06 4.711E-06
GMB 1.690E-04 1.695E-04 3.622E-04 3.664E-04 7.302E-04

```

```

SUBCKT X2 X2 X2 X2 X2
ELEMENT 2:M21 2:M22 2:M23 2:M24 2:M25
MODEL 0:CMOSN 0:CMOSN 0:CMOSP 0:CMOSP 0:CMOSN
ID 1.024E-04 1.036E-04 -1.024E-04 -1.036E-04 2.061E-04
IBS -2.079E-14 -2.079E-14 0. 0. 0.
IBD -2.509E-14 -2.267E-14 7.913E-15 1.033E-14 -2.079E-14
VGS 1.008E+00 1.008E+00 -7.913E-01 -7.913E-01 7.911E-01
VDS 4.300E-01 1.878E-01 -7.913E-01 -1.033E+00 2.078E+00
VBS -2.078E+00 -2.078E+00 0. 0. 0.
VTH 9.155E-01 9.155E-01 -7.000E-01 -7.000E-01 7.000E-01
VDSAT 9.259E-02 9.338E-02 -9.129E-02 -9.129E-02 9.108E-02
BETA 2.390E-02 2.377E-02 2.459E-02 2.487E-02 4.968E-02
GAM EFF 2.500E-01 2.500E-01 2.500E-01 2.500E-01 2.500E-01
GM 2.213E-03 2.219E-03 2.245E-03 2.270E-03 4.525E-03
GDS 2.434E-06 2.476E-06 4.833E-06 4.833E-06 4.711E-06
GMB 1.690E-04 1.695E-04 3.622E-04 3.664E-04 7.302E-04

```

```

SUBCKT X3 X3 X3 X3 X3
ELEMENT 3:M31 3:M32 3:M33 3:M34 3:M35
MODEL 0:CMOSP 0:CMOSP 0:CMOSN 0:CMOSN 0:CMOSP
ID -1.059E-04 -1.064E-04 1.059E-04 1.064E-04 -2.123E-04
IBS 2.096E-14 2.096E-14 0. 0. 0.
IBD 2.506E-14 2.290E-14 -7.937E-15 -1.010E-14 2.096E-14
VGS -1.010E+00 -1.011E+00 7.937E-01 7.937E-01 -7.902E-01
VDS -4.106E-01 -1.939E-01 7.937E-01 1.010E+00 -2.095E+00
VBS 2.095E+00 2.095E+00 0. 0. 0.
VTH -9.168E-01 -9.168E-01 7.000E-01 7.000E-01 -7.000E-01
VDSAT -9.365E-02 -9.438E-02 9.372E-02 9.372E-02 -9.019E-02
BETA 2.415E-02 2.390E-02 2.411E-02 2.423E-02 5.220E-02
GAM EFF 2.500E-01 2.500E-01 2.500E-01 2.500E-01 2.500E-01
GM 2.261E-03 2.255E-03 2.260E-03 2.271E-03 4.708E-03
GDS 5.086E-06 5.166E-06 2.494E-06 2.494E-06 9.435E-06
GMB 1.722E-04 1.717E-04 3.646E-04 3.665E-04 7.598E-04

```

```

SUBCKT X4 X4 X4 X4 X4
ELEMENT 4:M31 4:M32 4:M33 4:M34 4:M35
MODEL 0:CMOSP 0:CMOSP 0:CMOSN 0:CMOSN 0:CMOSP
ID -1.059E-04 -1.064E-04 1.059E-04 1.064E-04 -2.123E-04
IBS 2.096E-14 2.096E-14 0. 0. 0.
IBD 2.506E-14 2.290E-14 -7.937E-15 -1.010E-14 2.096E-14
VGS -1.010E+00 -1.011E+00 7.937E-01 7.937E-01 -7.902E-01
VDS -4.106E-01 -1.939E-01 7.937E-01 1.010E+00 -2.095E+00
VBS 2.095E+00 2.095E+00 0. 0. 0.
VTH -9.168E-01 -9.168E-01 7.000E-01 7.000E-01 -7.000E-01
VDSAT -9.365E-02 -9.438E-02 9.372E-02 9.372E-02 -9.019E-02
BETA 2.415E-02 2.390E-02 2.411E-02 2.423E-02 5.220E-02
GAM EFF 2.500E-01 2.500E-01 2.500E-01 2.500E-01 2.500E-01
GM 2.261E-03 2.255E-03 2.260E-03 2.271E-03 4.708E-03
GDS 5.086E-06 5.166E-06 2.494E-06 2.494E-06 9.435E-06
GMB 1.722E-04 1.717E-04 3.646E-04 3.665E-04 7.598E-04

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(10)/VIP = 3.488E+07
INPUT RESISTANCE AT VIP = 1.000E+20
OUTPUT RESISTANCE AT V(10) = 1.519E+10

```

ACTIVE FOLDED CASCODE OP AMP (NEW ZERO-BIAS THRESHOLDS)

```

*****
VDD 100 0 1.65
VSS 200 0 -1.65
* OP AMP
M1 11 1 5 100 CMOSP W=300U L=1U
M2 12 2 5 100 CMOSP W=300U L=1U
M1A 40 61 11 200 CMOSN W=100U L=1U
M2A 10 62 12 200 CMOSN W=100U L=1U
M3 3 40 100 100 CMOSP W=300U L=1U
M4 4 40 100 100 CMOSP W=300U L=1U
M3A 40 63 3 100 CMOSP W=300U L=1U
M4A 10 64 4 100 CMOSP W=300U L=1U
M5 5 51 100 100 CMOSP W=600U L=1U
M11 11 54 200 200 CMOSN W=200U L=1U
M12 12 54 200 200 CMOSN W=200U L=1U

```

* AUXILIARY AMPLIFIER SUBCIRCUITS

```

.SUBCKT AMP1 (21 22 24 26 100 200)
*E1 24 0 21 22 100
M21 23 21 25 200 CMOSN W=100U L=1U
M22 24 22 25 200 CMOSN W=100U L=1U
M23 23 23 100 100 CMOSP W=300U L=1U
M24 24 23 100 100 CMOSP W=300U L=1U
M25 25 26 200 200 CMOSN W=200U L=1U
.ENDS AMP1

```

.SUBCKT AMP2 (31 32 34 36 100 200)

```

*E2 34 0 31 32 100
M31 33 31 35 100 CMOSP W=300U L=1U
M32 34 32 35 100 CMOSP W=300U L=1U
M33 33 33 200 200 CMOSN W=100U L=1U
M34 34 33 200 200 CMOSN W=100U L=1U
M35 35 36 100 100 CMOSP W=600U L=1U
.ENDS AMP2

```

* AUXILIARY AMPLIFIERS

```

X1 52 3 63 54 100 200 AMP1
X2 52 4 64 54 100 200 AMP1
X3 53 11 61 51 100 200 AMP2
X4 53 12 62 51 100 200 AMP2

```

* BIAS GENERATOR

```

IBIAS 100 101 25U
M101 101 101 54 200 CMOSN W=25U L=1U
M102 54 54 200 200 CMOSN W=25U L=1U
M103 103 54 200 200 CMOSN W=25U L=1U
M104 105 101 103 200 CMOSN W=25U L=1U
M105 105 105 52 100 CMOSP W=25U L=1U
M106 52 105 100 100 CMOSP W=5U L=1U
M107 51 51 100 100 CMOSP W=75U L=1U
M108 108 108 51 100 CMOSP W=75U L=1U
M109 108 101 110 200 CMOSN W=25U L=1U
M110 110 54 200 200 CMOSN W=25U L=1U
M111 111 51 100 100 CMOSP W=75U L=1U
M112 113 108 111 100 CMOSP W=75U L=1U
M113 113 113 53 200 CMOSN W=25U L=1U
M114 53 113 200 200 CMOSN W=2.5U L=1U
CL 10 0 4P

```

.MODEL CMOSN NMOS LEVEL=1

```

+ TOX=0.8E-08 VTO=0.6 KP=194U LD=0.09U LAMBDA=0.024 GAMMA=0.25

```

.MODEL CMOSP PMOS LEVEL=1

```

+ TOX=0.8E-08 VTO=-0.8 KP=64.7U LD=0.09U LAMBDA=0.049 GAMMA=0.25

```

```

VIP 1 0 0 AC 1
VIN 2 0 0

```

.OPTIONS NOPAGE NOMOD

```

.WIDTH OUT=80

```

```

.OP

```

```

.TF V(10) VIP

```

```

.END

```

**** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:1	= 0. 0:2	= 0. 0:3	= 1.476E+00		
+0:4	= 1.476E+00 0:5	= 9.751E-01 0:10	= 7.591E-01		
+0:11	= -1.457E+00 0:12	= -1.457E+00 0:40	= 7.591E-01		
+0:51	= 7.600E-01 0:52	= 1.436E+00 0:53	= -1.456E+00		
+0:54	= -9.588E-01 0:61	= -7.390E-01 0:62	= -7.390E-01		
+0:63	= 5.600E-01 0:64	= 5.600E-01 0:100	= 1.650E+00		
+0:101	= -1.773E-01 0:103	= -9.582E-01 0:105	= 4.494E-01		
+0:108	= -2.412E-01 0:110	= -9.589E-01 0:111	= 7.591E-01		
+0:113	= -7.360E-01 0:200	= -1.650E+00 1:23	= 7.587E-01		
+1:25	= 5.211E-01 2:23	= 7.587E-01 2:25	= 5.211E-01		
+3:33	= -9.566E-01 3:35	= -3.537E-01 4:33	= -9.566E-01		
+4:35	= -3.537E-01				

**** MOSFETS

SUBCKT	X1					
ELEMENT	0:M1	0:M2	0:M1A	0:M2A	0:M3	
MODEL	0:CMOSP	0:CMOSP	0:CMOSH	0:CMOSH	0:CMOSP	
ID	-9.899E-05	-9.899E-05	9.866E-05	9.866E-05	-9.866E-05	
IBS	6.749E-15	6.749E-15	-1.930E-15	-1.930E-15	0.	
IBD	3.107E-14	3.107E-14	-2.409E-14	-2.409E-14	1.740E-15	
VGS	-9.751E-01	-9.751E-01	7.180E-01	7.180E-01	-8.909E-01	
VDS	-2.432E+00	-2.432E+00	2.216E+00	2.216E+00	-1.740E-01	
VBS	6.749E-01	6.749E-01	-1.930E-01	-1.930E-01	0.	
VTH	-8.886E-01	-8.886E-01	6.290E-01	6.290E-01	-8.000E-01	
VDSAT	-8.645E-02	-8.645E-02	8.899E-02	8.899E-02	-9.091E-02	
BETA	2.649E-02	2.649E-02	2.492E-02	2.492E-02	2.387E-02	
GAM EFF	2.500E-01	2.500E-01	2.500E-01	2.500E-01	2.500E-01	
GM	2.290E-03	2.290E-03	2.217E-03	2.217E-03	2.170E-03	
GDS	4.334E-06	4.334E-06	2.248E-06	2.248E-06	4.793E-06	
GMB	2.535E-04	2.535E-04	3.112E-04	3.112E-04	3.502E-04	
SUBCKT	X2					
ELEMENT	0:M4	0:M3A	0:M4A	0:M5	0:M11	
MODEL	0:CMOSP	0:CMOSP	0:CMOSP	0:CMOSP	0:CMOSH	
ID	-9.866E-05	-9.866E-05	-9.866E-05	-1.980E-04	1.976E-04	
IBS	0.	1.740E-15	1.740E-15	0.	0.	
IBD	1.740E-15	8.909E-15	8.909E-15	6.749E-15	-1.930E-15	
VGS	-8.909E-01	-9.160E-01	-9.160E-01	-8.900E-01	6.912E-01	
VDS	-1.740E-01	-7.169E-01	-7.169E-01	-6.749E-01	1.930E-01	
VBS	0.	1.740E-01	1.740E-01	0.	0.	
VTH	-8.000E-01	-8.263E-01	-8.263E-01	-8.000E-01	6.000E-01	
VDSAT	-9.091E-02	-8.974E-02	-8.974E-02	-8.998E-02	9.119E-02	
BETA	2.387E-02	2.450E-02	2.450E-02	4.891E-02	4.754E-02	
GAM EFF	2.500E-01	2.500E-01	2.500E-01	2.500E-01	2.500E-01	
GM	2.170E-03	2.199E-03	2.199E-03	4.401E-03	4.335E-03	
GDS	4.793E-06	4.670E-06	4.670E-06	9.390E-06	4.722E-06	
GMB	3.502E-04	3.124E-04	3.124E-04	7.101E-04	6.995E-04	
SUBCKT	X3					
ELEMENT	0:M12	0:M101	0:M102	0:M103	0:M104	
MODEL	0:CMOSH	0:CMOSH	0:CMOSH	0:CMOSH	0:CMOSH	
ID	1.976E-04	2.500E-05	2.500E-05	2.500E-05	2.500E-05	
IBS	0.	-6.912E-15	0.	0.	-6.918E-15	
IBD	-1.930E-15	-1.473E-14	-6.912E-15	-6.918E-15	-2.099E-14	
VGS	6.912E-01	7.815E-01	6.912E-01	6.912E-01	7.809E-01	
VDS	1.930E-01	7.815E-01	6.912E-01	6.918E-01	1.407E+00	
VBS	0.	-6.912E-01	0.	0.	-6.918E-01	
VTH	6.000E-01	6.904E-01	6.000E-01	6.000E-01	6.905E-01	
VDSAT	9.119E-02	9.109E-02	9.119E-02	9.119E-02	9.043E-02	
BETA	4.754E-02	6.026E-03	6.013E-03	6.013E-03	6.114E-03	
GAM EFF	2.500E-01	2.500E-01	2.500E-01	2.500E-01	2.500E-01	
GM	4.335E-03	5.489E-04	5.489E-04	5.483E-04	5.529E-04	
GDS	4.722E-06	5.890E-07	5.902E-07	5.902E-07	5.804E-07	
GMB	6.995E-04	6.038E-05	8.848E-05	8.848E-05	6.081E-05	
SUBCKT	X4					
ELEMENT	0:M105	0:M106	0:M107	0:M108	0:M109	
MODEL	0:CMOSP	0:CMOSP	0:CMOSP	0:CMOSP	0:CMOSH	
ID	-2.500E-05	-2.500E-05	-2.500E-05	-2.500E-05	2.500E-05	
IBS	2.133E-15	0.	0.	8.900E-15	-6.911E-15	
IBD	1.201E-14	2.133E-15	8.900E-15	1.891E-14	-1.409E-14	
VGS	-9.873E-01	-1.200E+00	-8.900E-01	-1.001E+00	7.816E-01	
VDS	-9.873E-01	-2.133E-01	-8.900E-01	-1.001E+00	7.176E-01	
VBS	2.133E-01	0.	0.	8.900E-01	-6.911E-01	
VTH	-8.318E-01	-8.000E-01	-8.000E-01	-9.115E-01	6.904E-01	
VDSAT	-1.555E-01	-2.133E-01	-8.998E-02	-8.974E-02	9.116E-02	
BETA	2.068E-03	3.986E-04	6.176E-03	6.208E-03	6.017E-03	
GAM EFF	2.500E-01	2.500E-01	2.500E-01	2.500E-01	2.500E-01	
GM	3.216E-04	8.504E-05	5.557E-04	5.571E-04	5.485E-04	
GDS	1.168E-06	7.588E-05	1.174E-06	1.168E-06	5.898E-07	
GMB	4.457E-05	1.372E-05	8.967E-05	5.705E-05	6.034E-05	
SUBCKT	X5					
ELEMENT	0:M110	0:M111	0:M112	0:M113	0:M114	
MODEL	0:CMOSH	0:CMOSP	0:CMOSP	0:CMOSH	0:CMOSH	
ID	2.500E-05	-2.500E-05	-2.500E-05	2.500E-05	2.500E-05	
IBS	0.	0.	8.909E-15	-1.938E-15	0.	
IBD	-6.911E-15	8.909E-15	2.386E-14	-9.140E-15	-1.938E-15	
VGS	6.912E-01	-8.900E-01	-1.000E+00	7.202E-01	9.140E-01	
VDS	6.911E-01	-8.909E-01	-1.495E+00	7.202E-01	1.938E-01	
VBS	0.	0.	8.909E-01	-1.938E-01	0.	
VTH	6.000E-01	-8.000E-01	-9.116E-01	6.291E-01	6.000E-01	
VDSAT	9.119E-02	-8.998E-02	-8.873E-02	9.116E-02	1.938E-01	
BETA	6.013E-03	6.176E-03	6.351E-03	6.017E-03	5.942E-04	
GAM EFF	2.500E-01	2.500E-01	2.500E-01	2.500E-01	2.500E-01	
GM	5.483E-04	5.557E-04	5.635E-04	5.485E-04	1.151E-04	
GDS	5.902E-07	1.174E-06	1.141E-06	5.898E-07	7.205E-05	
GMB	8.848E-05	8.968E-05	5.769E-05	7.696E-05	1.858E-05	

SUBCKT	X1					
ELEMENT	1:M21	1:M22	1:M23	1:M24	1:M25	
MODEL	0:CMOSH	0:CMOSH	0:CMOSP	0:CMOSP	0:CMOSH	
ID	1.030E-04	1.040E-04	-1.030E-04	-1.040E-04	2.070E-04	
IBS	-2.171E-14	-2.171E-14	0.	0.	0.	
IBD	-2.409E-14	-2.210E-14	8.913E-15	1.090E-14	-2.171E-14	
VGS	9.156E-01	9.549E-01	-8.913E-01	-8.913E-01	6.912E-01	
VDS	2.376E-01	3.887E-02	-8.913E-01	-1.090E+00	2.171E+00	
VBS	-2.171E+00	-2.171E+00	0.	0.	0.	
VTH	8.225E-01	8.225E-01	-8.000E-01	-8.000E-01	6.000E-01	
VDSAT	9.305E-02	3.887E-02	-9.132E-02	-9.132E-02	9.119E-02	
BETA	2.379E-02	2.368E-02	2.470E-02	2.494E-02	4.978E-02	
GAM EFF	2.500E-01	2.500E-01	2.500E-01	2.500E-01	2.500E-01	
GM	2.214E-03	9.205E-04	2.256E-03	2.277E-03	4.540E-03	
GDS	2.458E-06	2.217E-03	4.836E-06	4.836E-06	4.722E-06	
GMB	1.663E-04	6.912E-05	3.641E-04	3.675E-04	7.326E-04	

SUBCKT	X2					
ELEMENT	2:M21	2:M22	2:M23	2:M24	2:M25	
MODEL	0:CMOSH	0:CMOSH	0:CMOSP	0:CMOSP	0:CMOSH	
ID	1.030E-04	1.040E-04	-1.030E-04	-1.040E-04	2.070E-04	
IBS	-2.171E-14	-2.171E-14	0.	0.	0.	
IBD	-2.409E-14	-2.210E-14	8.913E-15	1.090E-14	-2.171E-14	
VGS	9.156E-01	9.549E-01	-8.913E-01	-8.913E-01	6.912E-01	
VDS	2.376E-01	3.887E-02	-8.913E-01	-1.090E+00	2.171E+00	
VBS	-2.171E+00	-2.171E+00	0.	0.	0.	
VTH	8.225E-01	8.225E-01	-8.000E-01	-8.000E-01	6.000E-01	
VDSAT	9.305E-02	3.887E-02	-9.132E-02	-9.132E-02	9.119E-02	
BETA	2.379E-02	2.368E-02	2.470E-02	2.494E-02	4.978E-02	
GAM EFF	2.500E-01	2.500E-01	2.500E-01	2.500E-01	2.500E-01	
GM	2.214E-03	9.205E-04	2.256E-03	2.277E-03	4.540E-03	
GDS	2.458E-06	2.217E-03	4.836E-06	4.836E-06	4.722E-06	
GMB	1.663E-04	6.912E-05	3.641E-04	3.675E-04	7.326E-04	

SUBCKT	X3					
ELEMENT	3:M31	3:M32	3:M33	3:M34	3:M35	
MODEL	0:CMOSP	0:CMOSP	0:CMOSH	0:CMOSH	0:CMOSP	
ID	-1.050E-04	-1.055E-04	1.050E-04	1.055E-04	-2.105E-04	
IBS	2.004E-14	2.004E-14	0.	0.	0.	
IBD	2.607E-14	2.389E-14	-6.934E-15	-9.110E-15	2.004E-14	
VGS	-1.102E+00	-1.103E+00	6.934E-01	6.934E-01	-8.900E-01	
VDS	-6.029E-01	-3.853E-01	6.934E-01	9.110E-01	-2.003E+00	
VBS	2.003E+00	2.003E+00	0.	0.	0.	
VTH	-1.009E+00	-1.009E+00	6.000E-01	6.000E-01	-8.000E-01	
VDSAT	-9.281E-02	-9.353E-02	9.342E-02	9.342E-02	-8.998E-02	
BETA	2.437E-02	2.412E-02	2.405E-02	2.418E-02	5.199E-02	
GAM EFF	2.500E-01	2.500E-01	2.500E-01	2.500E-01	2.500E-01	
GM	2.262E-03	2.256E-03	2.247E-03	2.259E-03	4.678E-03	
GDS	4.995E-06	5.074E-06	2.478E-06	2.478E-06	9.390E-06	
GMB	1.752E-04	1.748E-04	3.626E-04	3.645E-04	7.549E-04	

SUBCKT	X4					
ELEMENT	4:M31	4:M32	4:M33	4:M34	4:M35	
MODEL	0:CMOSP	0:CMOSP	0:CMOSH	0:CMOSH	0:CMOSP	
ID	-1.050E-04	-1.055E-04	1.050E-04	1.055E-04	-2.105E-04	
IBS	2.004E-14	2.004E-14	0.	0.	0.	
IBD	2.607E-14	2.389E-14	-6.934E-15	-9.110E-15	2.004E-14	
VGS	-1.102E+00	-1.103E+00	6.934E-01	6.934E-01	-8.900E-01	
VDS	-6.029E-01	-3.853E-01	6.934E-01	9.110E-01	-2.003E+00	
VBS	2.003E+00	2.003E+00	0.	0.	0.	
VTH	-1.009E+00	-1.009E+00	6.000E-01	6.000E-01	-8.000E-01	
VDSAT	-9.281E-02	-9.353E-02	9.342E-02	9.342E-02	-8.998E-02	
BETA	2.437E-02	2.412E-02	2.405E-02	2.418E-02	5.199E-02	
GAM EFF	2.500E-01	2.500E-01	2.500E-01	2.500E-01	2.500E-01	
GM	2.262E-03	2.256E-03	2.247E-03	2.259E-03	4.678E-03	
GDS	4.995E-06	5.074E-06	2.478E-06	2.478E-06	9.390E-06	
GMB	1.752E-04	1.748E-04	3.626E-04	3.645E-04	7.549E-04	

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(10)/VIP	=	3.492E+05
INPUT RESISTANCE AT VIP	=	1.000E+20
OUTPUT RESISTANCE AT V(10)	=	1.525E+08

6.23

The limiting branch includes M_{107} , M_{108} , M_{109} , and M_{110} because

$|V_{DS}|$ for three of these four transistors includes a $|V_t|$

$$|V_{DS_{107}}| = |V_{t_{107}}| + |V_{ov_{107}}|$$

$$|V_{DS_{108}}| = |V_{t_{108}}| + |V_{ov_{108}}|$$

$$V_{DS_{110}} = V_{t_{102}} + V_{ov_{102}} \text{ if } V_{GS_{101}} = V_{GS_{109}}$$

No other branch includes more than two $|V_t|$ terms.

Since $|V_{DS}|$ of M_{107} , M_{108} , and M_{110} are set to a $|V_t|$ above $|V_{ov}|$,

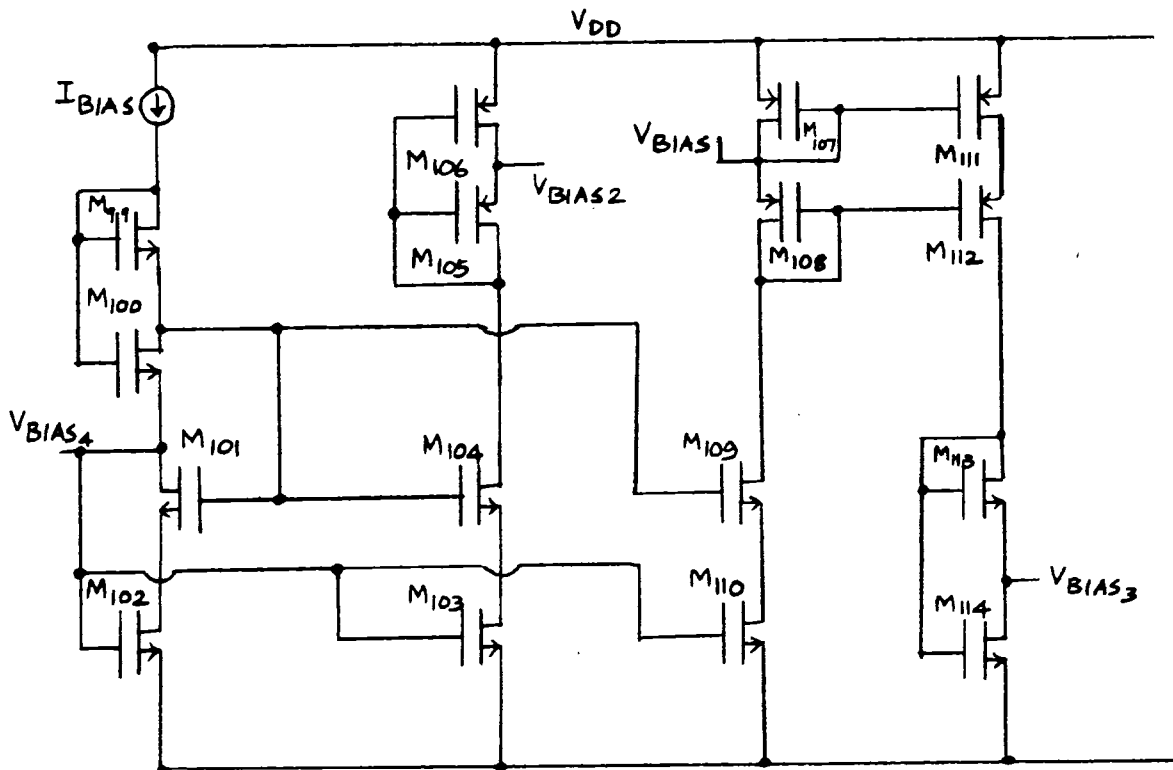
these transistors stay in the active region as $|V_{ov}|$ is increased.

Therefore, M_{109} enters the triode region first because its drain-source voltage is determined by the power-supply voltages

and the drain-source voltages of M_{107} , M_{108} , and M_{110} as follows

$$V_{DS_{109}} = V_{DD} - (-V_{SS}) - |V_{t_{107}}| - |V_{ov_{107}}| - |V_{t_{108}}| - |V_{ov_{108}}| - V_{t_{102}} - V_{ov_{102}}$$

To increase the allowed $|V_{ov}|$, use a sooch cascode



If $\left(\frac{W}{L}\right)_{100}$ is adjusted so that

$$V_{DS100} = V_{OV110} + 0.1 \text{ V}$$

$$\text{Then, } V_{DS110} = V_{OV110} + 0.1 \text{ V}$$

instead of

$$V_{DS110} = V_{t102} + V_{OV102} \text{ in the previous}$$

circuit. Assuming $V_{OV110} = V_{OV102}$,

the sooch cascode reduces

$$V_{DS110} \text{ if } V_{t102} > 0.1 \text{ V}$$

In turn, this increases V_{DS109} for a fixed $|V_{OV}|$, which means that a larger $|V_{OV}|$ is required to push M_{109} into the triode region. The key disadvantage of the new circuit is that it reduces the voltage across the I_{BIAS} generator.

CM input range :

To keep the transistor that forms I_1 in the active region,

$$V_{ic} > -V_{SS} + V_{OVn} + V_{OVp} + V_{t1}$$

$$V_{ic} > -V_{SS} + V_{t1} + 2V_{OVn}$$

To keep M_1 in the active region,

$$V_{GD1} < V_{t1}$$

$$V_{G1} = V_{ic}$$

$$V_{D1} = -V_{SS} + V_{t3} + V_{OV3} + V$$

$$= -V_{SS} + V_{t3} + V_{OVn} + V$$

$$V_{G1} - V_{D1} < V_{t1}$$

$$V_{ic} < V_{D1} + V_{t1}$$

$$< -V_{SS} + V_{t3} + V_{OVn} + V + V_{t1}$$

So the CM input range is :

$$-V_{SS} + V_{t1} + 2V_{OVn} < V_{ic} < -V_{SS} + V_{t3} + V_{OVn} + V + V_{t1}$$

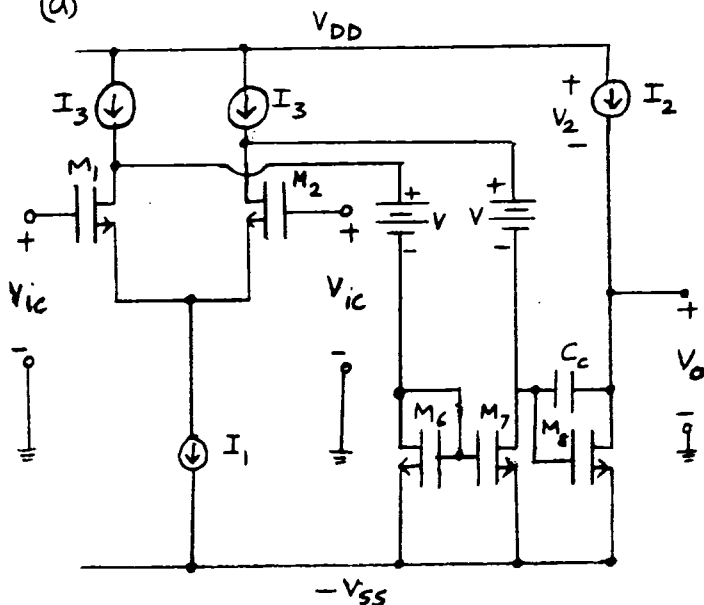
output swing :

$$-V_{SS} + V_{OVn} < V_o < V_{DD} - |V_{OVp}|$$

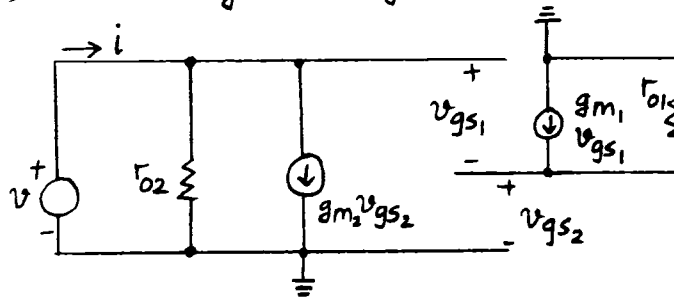
because $V_{DS8} > V_{OVn}$ is required to operate M_8 in the active region and $V_2 > |V_{OVp}|$ is required to operate the transistor forming I_2 in the active region.

6.24

(a)



(b) small-signal diagram:



$$R_i = \frac{v}{i}$$

$$i = \frac{v}{r_{o2}} + g_{m2} v_{gs2}$$

Since M_1 is a source-follower $v_{gs2} \approx v$

$$i \approx v \left(\frac{1}{r_{o2}} + g_{m2} \right)$$

$$\frac{v}{i} \approx \frac{1}{g_{m2} + \frac{1}{r_{o2}}} \approx \frac{1}{g_{m2}} < 1 \text{ k}\Omega$$

$$g_{m2} = \sqrt{2(100 \mu\text{A})(194 \mu\text{A}/\text{V}^2)(\frac{W}{L})_2}$$

$$1000 \frac{\mu\text{A}}{\text{V}} = \frac{1}{1 \text{ k}\Omega} < \sqrt{2(100 \mu\text{A})(194 \frac{\mu\text{A}}{\text{V}^2})(\frac{W}{L})_2}$$

$$\left(\frac{W}{L}\right)_2 > 25.8$$

$$\begin{aligned} V_{GS2} &= V_{t2} + V_{OV2} \\ &= 0.6 + \sqrt{\frac{2(100)}{194(26)}} = 0.8 \text{ V} \end{aligned}$$

$$V_{GS1} + V_{GS2} = V$$

$$V_{GS1} = V - V_{GS2} = 1.5 - 0.8 = 0.7 \text{ V}$$

$$= \underbrace{V_{t1}}_{0.6 \text{ V}} + V_{OV1}$$

$$\text{SO, } V_{OV1} = 0.7 - 0.6 = 0.1 \text{ V}; I_{D1} = \frac{K'}{2} \left(\frac{W}{L}\right)_1 V_{OV1}^2$$

$$\left(\frac{W}{L}\right)_1 = \frac{2 I_{D1}}{K' V_{OV1}^2} = \frac{2(100)}{194(0.1)^2} \approx 100$$

MOS FLOATING LEVEL SHIFT

```

VDD 100 0 1.65
VSS 200 0 -1.65
M1 100 3 4 4 CMOSN W=100U L=1U
M2 3 4 5 200 CMOSN W=26U L=1U
VM2 5 200 0
IB 4 200 100U
VI 3 200 1.5
.MODEL CMOSN NMOS LEVEL=1 VTO=0.6 KP=194U
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.DC VI 0 2 0.1
.PLOT DC I(VM2)
.TF V(3) VI
.END

```

***** DC TRANSFER CURVES THOM= 27.000 TEMP= 27.000

VOLT	I(VM2)				
0.	0.	5.000E-04	1.000E-03	1.500E-03	2.000E-03
0.	-2.02E-28 A				
1.000E-01	1.00E-13 A	+	+	+	+
2.000E-01	2.00E-13 A	+	+	+	+
3.000E-01	3.00E-13 A	+	+	+	+
4.000E-01	4.00E-13 A	+	+	+	+
5.000E-01	5.00E-13 A	+	+	+	+
6.000E-01	6.00E-13 A	+	+	+	+
7.000E-01	7.00E-13 A	+	+	+	+
8.000E-01	8.00E-13 A	+	+	+	+
9.000E-01	9.00E-13 A	+	+	+	+
1.000E+00	1.00E-12 A				
1.100E+00	1.10E-12 A	+	+	+	+
1.200E+00	1.20E-12 A	+	+	+	+
1.300E+00	1.30E-12 A	+	+	+	+
1.400E+00	2.45E-05 A	+	+	+	+
1.500E+00	9.93E-05 A	+	+	+	+
1.600E+00	2.25E-04 A	+	+	+	+
1.700E+00	4.00E-04 A	+	+	+	+
1.800E+00	6.27E-04 A	+	+	+	+
1.900E+00	9.03E-04 A	+	+	+	+
2.000E+00	1.23E-03 A				

**** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:3	=-1.500E-01	0:4	=-8.515E-01	0:5	=-1.650E+00
+0:100	= 1.650E+00	0:200	=-1.650E+00		

SUBCKT

ELEMENT	0:M1	0:M2
MODEL	0:CMOSN	0:CMOSN
ID	1.000E-04	9.934E-05
IBS	0.	0.
IBD	-2.502E-14	-1.500E-14
VGS	7.015E-01	7.985E-01
VDS	2.501E+00	1.500E+00
VBS	0.	0.
VTH	6.000E-01	6.000E-01
VDSAT	1.015E-01	1.985E-01
BETA	1.940E-02	5.044E-03
GAM EFF	0.	0.
GM	1.970E-03	1.001E-03
GDS	0.	0.
GDB	0.	0.

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(3)/VI		= 1.000E+00
INPUT RESISTANCE AT VI		= 9.989E+02
OUTPUT RESISTANCE AT V(3)		= 0.

6.25

$$I_{REF} = \frac{V_{CC} - V_{EE} - 2V_{BE}}{39 \text{ k}\Omega} = 0.48 \text{ mA}$$

$$V_T \ln \frac{I_{REF}}{I_1} = (5 \text{ k}\Omega) I_1$$

By trial, $I_1 = 17 \mu\text{A}$ and thus

$$I_{C1} = I_{C2} = 8.5 \mu\text{A}$$

The change is a decrease of $1 \mu\text{A}$

741 INPUT STAGE, VCC = 10 V (INFINITE VAF)

VCC 100 0 10

* USE A VOLTAGE-CONTROLLED VOLTAGE SOURCE TO SET VEE = -1(VCC)

EVEE 200 0 100 0 -1

Q1 7 8 10 NPN

Q2 7 9 11 NPN

Q3 12 6 10 PNP

Q4 16 6 11 PNP

Q5 12 13 14 NPN

Q6 16 13 15 NPN

Q7 100 12 13 NPN

Q8 7 7 100 PNP

Q9 6 7 100 PNP

Q10 6 4 5 NPN

Q11 4 4 200 NPN

Q12 3 3 100 PNP

R1 14 200 1K

R2 15 200 1K

R3 13 200 50K

R5 3 4 39K

R4 5 200 5K

VI1 8 0 0

VI2 9 0 0

.MODEL NPN NPN BF=250 IS=5E-15

.MODEL PNP PNP BF=50 IS=2E-15

.OPTIONS NOPAGE NOMOD

.WIDTH OUT=80

.OP

.DC VCC 10 15 5

.PRINT DC I(Q1) I(Q2)

.END

***** DC TRANSFER CHARACTERISTIC THOM= 27.000 TEMP= 27.000

VOLT CURRENT CURRENT

Q1 Q2

1.0000E+01 8.724E-06 8.709E-06

1.5000E+01 9.597E-06 9.582E-06

**** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

NODE =VOLTAGE NODE =VOLTAGE NODE =VOLTAGE

+0:3 = 9.322E+00 0:4 = -9.346E+00 0:5 = -9.912E+00

+0:6 = -1.124E+00 0:7 = 9.409E+00 0:8 = 0.

+0:9 = 0. 0:10 = -5.504E-01 0:11 = -5.503E-01

+0:12 = -8.884E+00 0:13 = -9.441E+00 0:14 = -9.991E+00

+0:15 = -9.991E+00 0:16 = -6.970E-01 0:100 = 1.000E+01

+0:200 = -1.000E+01

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT

ELEMENT 0:Q1 0:Q2 0:Q3 0:Q4

MODEL 0:NPN 0:NPN 0:PNP 0:PNP

IB 3.489E-08 3.484E-08 -1.717E-07 -2.017E-07

IC 8.724E-06 8.709E-06 -8.587E-06 -8.542E-06

VBE 5.504E-01 5.503E-01 -5.737E-01 -5.737E-01

VCE 9.959E+00 9.959E+00 -8.334E+00 -1.467E-01

SUBCKT

ELEMENT 0:Q5 0:Q6 0:Q7 0:Q8

MODEL 0:NPN 0:NPN 0:NPN 0:PNP

IB 3.417E-08 3.417E-08 4.477E-08 -3.352E-07

IC 8.542E-06 8.542E-06 1.119E-05 -1.676E-05

VBE 5.498E-01 5.498E-01 5.568E-01 -5.910E-01

VCE 1.106E+00 9.294E+00 1.944E+01 -5.910E-01

SUBCKT
ELEMENT 0:Q9 0:Q10 0:Q11 0:Q12
MODEL 0:PNP 0:NPN 0:NPN 0:PNP
IB -3.352E-07 6.854E-08 1.907E-06 -9.386E-06
IC -1.676E-05 1.714E-05 4.767E-04 -4.693E-04
VBE -5.910E-01 5.678E-01 6.539E-01 -6.772E-01
VCE -1.112E+01 8.789E+00 6.539E-01 -6.772E-01

741 INPUT STAGE, VCC = 10 V (FINITE VAF)

VCC 100 0 10

* USE A VOLTAGE-CONTROLLED VOLTAGE SOURCE TO SET VEE = -1(VCC)

EVEE 200 0 100 0 -1

Q1 7 8 10 NPN

Q2 7 9 11 NPN

Q3 12 6 10 PNP

Q4 16 6 11 PNP

Q5 12 13 14 NPN

Q6 16 13 15 NPN

Q7 100 12 13 NPN

Q8 7 7 100 PNP

Q9 6 7 100 PNP

Q10 6 4 5 NPN

Q11 4 4 200 NPN

Q12 3 3 100 PNP

R1 14 200 1K

R2 15 200 1K

R3 13 200 50K

R5 3 4 39K

R4 5 200 5K

VI1 8 0 0

VI2 9 0 0

.MODEL NPN NPN BF=250 IS=5E-15 VAF=130

.MODEL PNP PNP BF=50 IS=2E-15 VAF=50

.OPTIONS NOPAGE NOMOD

.WIDTH OUT=80

.OP

.DC VCC 10 15 5

.PRINT DC I(Q1) I(Q2)

.END

***** DC TRANSFER CHARACTERISTIC THOM= 27.000 TEMP= 27.000

VOLT CURRENT CURRENT

Q1 Q2

1.0000E+01 7.370E-06 7.348E-06

1.5000E+01 7.554E-06 7.534E-06

**** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

NODE =VOLTAGE NODE =VOLTAGE NODE =VOLTAGE

+0:3 = 9.322E+00 0:4 = -9.346E+00 0:5 = -9.912E+00

+0:6 = -1.109E+00 0:7 = 9.413E+00 0:8 = 0.

+0:9 = 0. 0:10 = -5.442E-01 0:11 = -5.441E-01

+0:12 = -8.894E+00 0:13 = -9.447E+00 0:14 = -9.992E+00

+0:15 = -9.992E+00 0:16 = -8.534E+00 0:100 = 1.000E+01

+0:200 = -1.000E+01

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT

ELEMENT 0:Q1 0:Q2 0:Q3 0:Q4

MODEL 0:NPN 0:NPN 0:PNP 0:PNP

IB 2.749E-08 2.741E-08 -1.258E-07 -1.262E-07

IC 7.370E-06 7.348E-06 -7.272E-06 -7.249E-06

VBE 5.442E-01 5.441E-01 -5.656E-01 -5.657E-01

VCE 9.957E+00 9.957E+00 -8.350E+00 -7.990E+00

SUBCKT

ELEMENT 0:Q5 0:Q6 0:Q7 0:Q8

MODEL 0:NPN 0:NPN 0:NPN 0:PNP

IB 2.881E-08 2.879E-08 3.867E-08 -2.830E-07

IC 7.233E-06 7.249E-06 1.107E-05 -1.415E-05

VBE 5.454E-01 5.454E-01 5.530E-01 -5.866E-01

VCE 1.098E+00 1.458E+00 1.944E+01 -5.866E-01

SUBCKT

ELEMENT 0:Q9 0:Q10 0:Q11 0:Q12

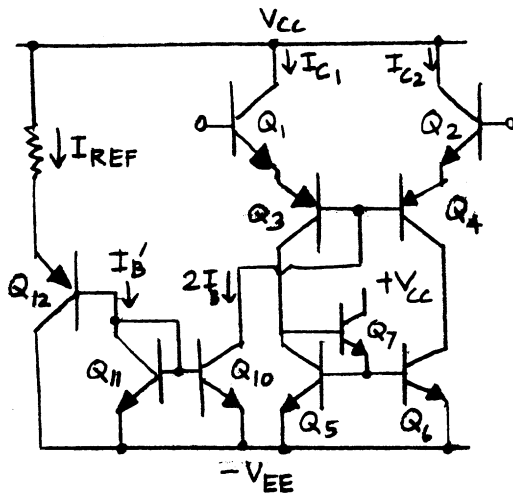
MODEL 0:PNP 0:NPN 0:NPN 0:PNP

IB -2.830E-07 6.539E-08 1.907E-06 -9.386E-06

IC -1.713E-05 1.738E-05 4.767E-04 -4.693E-04

VBE -5.866E-01 5.666E-01 6.539E-01 -6.772E-01

VCE -1.111E+01 8.802E+00 6.539E-01 -6.772E-01

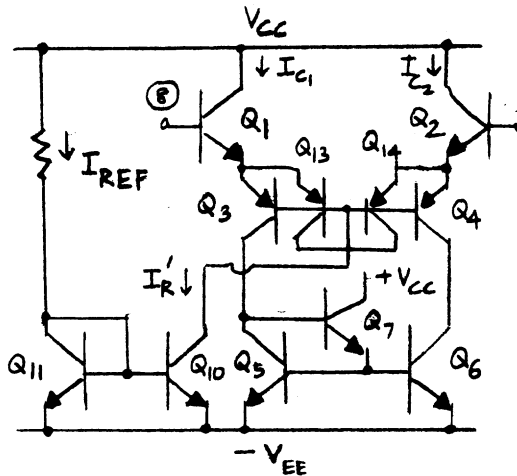
6.26
(a)

$$I_{C1} = I_{C2} = 10 \mu A \quad \beta_{PNP} = 50$$

$$I_B = \frac{I_{C1}}{1 + \beta_{PNP}} \quad \therefore 2I_B = 0.39 \mu A \approx I_B'$$

$$\therefore I_{REF} = (1 + \beta_{PNP}) I_B' = 20 \mu A$$

(b)



$$I_{C1} = I_{C2} = 10 \mu A$$

$$I_{E3} = I_{E13} = I_{E14} = I_{E4} \approx \frac{I_{C1}}{2} = 5 \mu A$$

$$I_{R'} = 2|I_{C3}| + 4|I_{B13}|$$

$$= 2 \left(\frac{5 \mu A}{1 + 50} \right) \cdot 50 + 4 \cdot \left(\frac{5 \mu A}{1 + 50} \right)$$

$$= 10.2 \mu A = I_{REF}$$

741 INPUT BIAS SCHEME (A)

VCC	100	0	15	
VBE	200	0	-15	
IREF	100	3	20U	
Q1	100	8	10	NPN
Q2	100	9	11	NPN
Q3	12	6	10	PNP
Q4	16	6	11	PNP
Q5	12	13	200	NPN
Q6	16	13	200	NPN
Q7	100	12	13	NPN
Q10	6	4	200	NPN
Q11	4	4	200	NPN
Q12	200	4	3	PNP

* WITH VIC = -12.6 V,

* VCE10 = VIC - VBE1 - |VBE3| - (-VEE)

* = -12.6 - 0.6 - 0.6 + 15 = 1.2 V

* THIS IS ENOUGH TO OPERATE Q10 IN THE FORWARD-ACTIVE REGION.

VI1 8 0 -12.6

VI2 9 0 -12.6 AC 1

.MODEL NPN NPN BF=250 IS=5E-15

.MODEL PNP PNP BF=50 IS=2E-15

.OPTIONS NOPAGE NOMOD

.WIDTH OUT=80

.OP

* VOUT IS USED TO MEASURE THE AC SHORT CIRCUIT OUTPUT

* CURRENT TO FIND GM.

* THE DC VALUE OF VOUT WAS GIVEN IN THE PROBLEM STATEMENT.

VOUT 16 200 1.6

.AC DEC 1 1 10

.PRINT AC IM(VOUT) IP(VOUT)

* THE TRANSCONDUCTANCE CAN ALSO BE MEASURED BY ELIMINATING

* THE VOLTAGE SOURCE CONNECTED AT THE OUTPUT AND THE

* AC ANALYSIS ABOVE, FINDING THE VOLTAGE GAIN AND OUTPUT

* RESISTANCE WITH A .TF STATEMENT AS SHOWN BELOW,

* AND CALCULATING GM = (VOLTAGE GAIN)/(OUTPUT RESISTANCE)

* THE RESULT IS GM = 1.736E4/9.237E7 = 188E-6 A/V

* .TF V(16) VI2

.END

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:3	=-1.393E+01	0:4	=-1.453E+01	0:6	=-1.373E+01
+0:8	=-1.260E+01	0:9	=-1.260E+01	0:10	=-1.315E+01
+0:11	=-1.315E+01	0:12	=-1.401E+01	0:13	=-1.444E+01
+0:16	=-1.340E+01	0:100	= 1.500E+01	0:200	=-1.500E+01

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT

ELEMENT	0:Q1	0:Q2	0:Q3	0:Q4	0:Q5
MODEL	0:NPN	0:NPN	0:PNP	0:PNP	0:NPN
IB	3.945E-08	3.945E-08	-1.942E-07	-1.949E-07	3.883E-08
IC	9.863E-06	9.863E-06	-9.708E-06	-9.707E-06	9.708E-06
VBE	5.536E-01	5.536E-01	-5.769E-01	-5.769E-01	5.532E-01
VCE	2.815E+01	2.815E+01	-8.651E-01	-2.464E-01	9.813E-01
VBC	-2.760E+01	-2.760E+01	2.883E-01	-3.304E-01	-4.282E-01
VS	-1.500E+01	-1.500E+01	1.373E+01	1.373E+01	1.401E+01
POWER	2.777E-04	2.777E-04	8.511E-06	2.505E-06	9.548E-06
BETAD	2.500E+02	2.500E+02	5.000E+01	4.981E+01	2.500E+02
GM	3.813E-04	3.813E-04	3.754E-04	3.753E-04	3.753E-04
RPI	6.555E+05	6.556E+05	1.332E+05	1.332E+05	6.660E+05
RX	0.	0.	0.	0.	0.
RO	5.520E+15	5.520E+15	1.441E+14	3.661E+07	8.563E+13
BETAAC	2.500E+02	2.500E+02	5.000E+01	4.999E+01	2.500E+02

```

SUBCKT
ELEMENT 0:Q6      0:Q7      0:Q10     0:Q11     0:Q12
MODEL   0:NPN     0:NPN     0:NPN     0:NPN     0:PMP
IB      3.883E-08  3.094E-10  1.556E-09  1.556E-09  -3.922E-07
IC      9.708E-06  7.735E-08  3.890E-07  3.890E-07  -1.961E-05
VBE     5.532E-01  4.282E-01  4.699E-01  4.699E-01  -5.950E-01
VCE     1.600E+00  2.944E+01  1.269E+00  4.699E-01  -1.065E+00
VBC     -1.046E+00 -2.901E+01 -7.996E-01  0.          4.699E-01
VS      1.340E+01 -1.500E+01  1.373E+01  1.453E+01  1.453E+01
POWER   1.555E-05  2.278E-06  4.947E-07  1.836E-07  2.112E-05
BETAD   2.500E+02  2.500E+02  2.500E+02  2.500E+02  5.000E+01
GM       3.753E-04  2.991E-06  1.504E-05  1.504E-05  7.581E-04
RPI      6.660E+05  8.359E+07  1.662E+07  1.662E+07  6.595E+04
RX       0.         0.         0.         0.         0.
RO       2.093E+14  5.803E+15  1.599E+14  5.172E+12  2.349E+14
BETAAAC 2.500E+02  2.500E+02  2.500E+02  2.500E+02  5.000E+01

```

```

***** AC ANALYSIS      TNOM= 27.000 TEMP= 27.000
FREQ  I MAG      I PHASE
      VOUT      VOUT
1.0000E+00  1.877E-04  4.174E-23
1.0000E+01  1.877E-04  4.174E-22

```

741 INPUT BIAS SCHEME (B)

```

VCC 100 0 15
VEE 200 0 -15
IREF 100 4 10.2U
Q1 100 8 10 NPN
Q2 100 9 11 NPN
Q3 12 6 10 PNP
Q4 16 6 11 PNP
Q5 12 13 200 NPN
Q6 16 13 200 NPN
Q7 100 12 13 NPN
Q10 6 4 200 NPN
Q11 4 4 200 NPN

```

```

* REMOVE Q12 FROM THE CIRCUIT.
* IT WAS ONLY NEEDED FOR PART (A).
Q12 200 200 200 PNP
Q13 6 6 10 PNP
Q14 6 6 11 PNP

```

```

* WITH VIC = -12.6 V,
* VCE10 = VIC - VBE1 - |VBE3| - (-VEE)
= -12.6 - 0.6 - 0.6 + 15 = 1.2 V
* THIS IS ENOUGH TO OPERATE Q10 IN THE FORWARD-ACTIVE REGION.
V11 8 0 -12.6
V12 9 0 -12.6 AC 1

```

```

.MODEL NPN NPN BF=250 IS=5E-15
.MODEL PNP PNP BF=50 IS=2E-15
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP

```

```

* VOUT IS USED TO MEASURE THE AC SHORT CIRCUIT OUTPUT
* CURRENT TO FIND GM.
* THE DC VALUE OF VOUT WAS GIVEN IN THE PROBLEM STATEMENT.
VOUT 16 200 1.6

```

```

.AC DEC 1 1 10
.PRINT AC IM(VOUT) IP(VOUT)

```

```

* THE TRANSCONDUCTANCE CAN ALSO BE MEASURED BY ELIMINATING
* THE VOLTAGE SOURCE CONNECTED AT THE OUTPUT AND THE
* AC ANALYSIS ABOVE, FINDING THE VOLTAGE GAIN AND OUTPUT
* RESISTANCE WITH A .TF STATEMENT AS SHOWN BELOW,
* AND CALCULATING GM = (VOLTAGE GAIN)/(OUTPUT RESISTANCE)
* THE RESULT IS GM = 1.942E4/2.065E8 = 94E-6 A/V
* THE TRANSCONDUCTANCE IS REDUCED HERE COMPARED
* TO THE TRANSCONDUCTANCE IN PART (A) BECAUSE
* THE COLLECTOR CURRENT OF Q13 AND Q14 HERE FLOWS
* IN Q10 AND DOES NOT CONTRIBUTE TO THE STAGE OUTPUT.
* .TF V(16) V12
.END

```

```

**** OPERATING POINT INFORMATION      TNOM= 27.000 TEMP= 27.000
NODE  =VOLTAGE      NODE  =VOLTAGE      NODE  =VOLTAGE
+0:3  = 0.          0:4  =-1.444E+01 0:6  =-1.371E+01
+0:8  =-1.260E+01 0:9  =-1.260E+01 0:10 =-1.315E+01
+0:11 =-1.315E+01 0:12 =-1.405E+01 0:13 =-1.446E+01
+0:16 =-1.340E+01 0:100 = 1.500E+01 0:200 =-1.500E+01

```

**** BIPOLAR JUNCTION TRANSISTORS

```

SUBCKT
ELEMENT 0:Q1      0:Q2      0:Q3      0:Q4      0:Q5
MODEL   0:NPN     0:NPN     0:PMP     0:PMP     0:NPN
IB      3.954E-08  3.954E-08 -9.729E-08 -9.765E-08 1.946E-08
IC      9.884E-06  9.884E-06 -4.865E-06 -4.864E-06 4.865E-06
VBE     5.536E-01  5.536E-01 -5.590E-01 -5.590E-01 5.353E-01
VCE     2.815E+01  2.815E+01 -9.008E-01 -2.464E-01 9.456E-01
VBC     -2.760E+01 -2.760E+01 3.418E-01 -3.126E-01 -4.103E-01
VS      -1.500E+01 -1.500E+01 1.371E+01 1.371E+01 1.405E+01
POWER   2.783E-04  2.783E-04 4.437E-06 1.253E-06 4.610E-06
BETAD   2.500E+02  2.500E+02 5.000E+01 4.981E+01 2.500E+02
GM       3.822E-04  3.822E-04 1.881E-04 1.881E-04 1.881E-04
RPI      6.541E+05  6.541E+05 2.658E+05 2.658E+05 1.329E+06
RX       0.         0.         0.         0.         0.
RO       5.520E+15  5.520E+15 1.709E+14 7.290E+07 8.205E+13
BETAAAC 2.500E+02  2.500E+02 5.000E+01 4.999E+01 2.500E+02

```

```

SUBCKT
ELEMENT 0:Q6      0:Q7      0:Q10     0:Q11     0:Q12
MODEL   0:NPN     0:NPN     0:NPN     0:NPN     0:PMP
IB      1.946E-08  1.550E-10 4.048E-08 4.048E-08 0.
IC      4.865E-06  3.876E-08 1.012E-05 1.012E-05 0.
VBE     5.353E-01  4.103E-01 5.542E-01 5.542E-01 0.
VCE     1.600E+00  2.946E+01 1.287E+00 5.542E-01 0.
VBC     -1.064E+00 -2.905E+01 -7.332E-01 0.         0.
VS      1.340E+01 -1.500E+01 1.371E+01 1.444E+01 1.500E+01
POWER   7.794E-06  1.142E-06 1.305E-05 5.631E-06 0.
BETAD   2.500E+02  2.500E+02 2.500E+02 2.500E+02 0.
GM       1.881E-04  1.499E-06 3.912E-04 3.912E-04 0.
RPI      1.329E+06  1.668E+08 6.390E+05 6.390E+05 6.466E+14
RX       0.         0.         0.         0.         0.
RO       2.129E+14  5.810E+15 1.466E+14 5.172E+12 1.293E+13
BETAAAC 2.500E+02  2.500E+02 2.500E+02 2.500E+02 0.

```

```

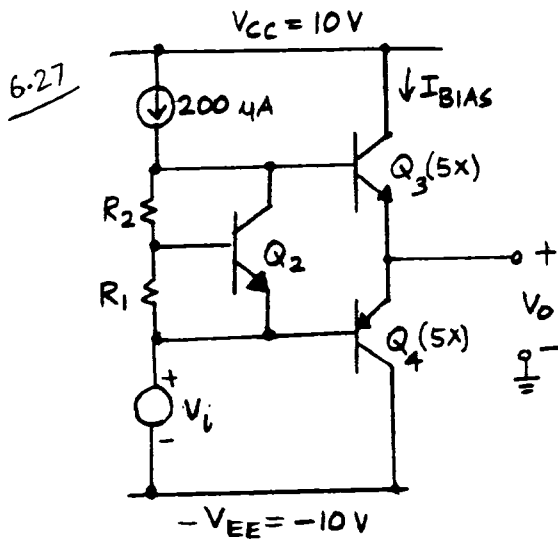
SUBCKT
ELEMENT 0:Q13     0:Q14
MODEL   0:PMP     0:PMP
IB      -9.729E-08 -9.730E-08
IC      -4.865E-06 -4.865E-06
VBE     -5.590E-01 -5.590E-01
VCE     -5.590E-01 -5.590E-01
VBC     0.          0.
VS      1.371E+01 1.371E+01
POWER   2.774E-06 2.774E-06
BETAD   5.000E+01 5.000E+01
GM       1.881E-04 1.881E-04
RPI      2.658E+05 2.658E+05
RX       0.         0.
RO       1.293E+13 1.293E+13
BETAAAC 5.000E+01 5.000E+01

```

```

***** AC ANALYSIS      TNOM= 27.000 TEMP= 27.000
FREQ  I MAG      I PHASE
      VOUT      VOUT
1.0000E+00  9.405E-05  8.873E-23
1.0000E+01  9.405E-05  8.873E-22

```



$$I_{BIAS} = 50 \mu A, I_S = 10^{-15} A, I_{C_2} = 200 \mu A$$

$$\therefore \frac{R_2}{R_1} = 0.77$$

From ①, If we choose $\frac{R_2}{R_1} = 1$

$$\text{then } I_{BIAS} = 5(I_{C_2})^{\frac{1}{2}(1 + \frac{R_2}{R_1})}$$

$$= 1000 \mu A = 1 \text{ mA}$$

and I_{BIAS} is independent of temperature. In general, if $\frac{R_2}{R_1} \neq 1$

then I_{BIAS} is dependent on temperature because I_S depends on temperature.

Neglect current flow through R_1 and R_2 from $200 \mu A$ source.

$$\therefore I_{C_2} = 200 \mu A, V_{BE_2} = V_T \ln \frac{I_{C_2}}{I_{S_2}}$$

$$V_{BE_4} + V_{BE_3} = V_{BE_2} + \frac{V_{BE_2}}{R_1} \times R_2$$

$$= \frac{V_T}{R_1} (R_1 + R_2) \ln \frac{I_{C_2}}{I_{S_2}}$$

$$= V_T \ln \left(\frac{I_{C_3} | I_{C_4}|}{I_{S_3} I_{S_4}} \right)$$

Areas of Q_3, Q_4 are 5 times of Q_1 and Q_2 . Therefore,

$$I_{S_1} = I_{S_2} = 10^{-15} A = I_S$$

$$I_{S_3} = I_{S_4} = 5 \times 10^{-15} A = 5 I_S$$

$$V_T \ln \left(\frac{I_{BIAS}^2}{25 I_S^2} \right) = V_T \left(1 + \frac{R_2}{R_1} \right) \ln \left(\frac{I_{C_2}}{I_S} \right)$$

$$\therefore I_{BIAS} = 5 I_S \left(\frac{I_{C_2}}{I_S} \right)^{\frac{1}{2}(1 + \frac{R_2}{R_1})}$$

$$= 5 (I_{C_2})^{\frac{1}{2}(1 + \frac{R_2}{R_1})} (I_S)^{\frac{1}{2}(1 - \frac{R_2}{R_1})}$$

→ ①

$$\frac{R_2}{R_1} = \frac{2 \ln \left(\frac{I_{BIAS}}{5 I_S} \right)}{\ln \left(\frac{I_{C_2}}{I_S} \right)} - 1$$

741 OUTPUT-STAGE BIAS SCHEME
 * BF=LARGE TO CHECK HAND CALCULATIONS

```
VCC 100 0 10
VBE 200 0 -10
IREF 100 3 200U
Q2 3 4 5 NPN
Q3 100 3 6 NPN 5
Q4 200 5 6 PNP 5
R1 4 5 100K
R2 3 4 77K
VI 5 200 9.404
.MODEL NPN NPN BF=10000 IS=1E-15
.MODEL PNP PNP BF=10000 IS=1E-15
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.END
```

```
**** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000
      NODE =VOLTAGE      NODE =VOLTAGE      NODE =VOLTAGE
+0:3      = 5.952E-01 0:4      = 7.614E-02 0:5      =-5.960E-01
+0:6      =-4.124E-04 0:100     = 1.000E+01 0:200     =-1.000E+01
```

```
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT 0:Q2      0:Q3      0:Q4
MODEL 0:NPN      0:NPN      0:PNP
IB 1.933E-08 5.008E-09 -5.008E-09
IC 1.933E-04 5.008E-05 -5.008E-05
VBE 6.721E-01 5.956E-01 -5.956E-01
VCE 1.191E+00 1.000E+01 -9.999E+00
BETAD 1.000E+04 1.000E+04 1.000E+04
```

741 OUTPUT-STAGE BIAS SCHEME
 * SET BF TO NORMAL VALUES AND RUN TEMPERATURE SWEEP

```
VCC 100 0 10
VBE 200 0 -10
IREF 100 3 200U
Q2 3 4 5 NPN
Q3 100 3 6 NPN 5
Q4 200 5 6 PNP 5
R1 4 5 100K
R2 3 4 77K
VI 5 200 9.404
.MODEL NPN NPN BF=250 IS=1E-15
.MODEL PNP PNP BF=50 IS=1E-15
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.TEMP -55 -35 -15 5 25 45 65 85 105 125
.END
```

```
**** OPERATING POINT INFORMATION THOM= 27.000 TEMP= -55.000
      NODE =VOLTAGE      NODE =VOLTAGE      NODE =VOLTAGE
+0:3      = 8.957E-01 0:4      = 2.135E-01 0:5      =-5.960E-01
+0:6      = 1.497E-01 0:100     = 1.000E+01 0:200     =-1.000E+01
```

```
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT 0:Q2      0:Q3      0:Q4
MODEL 0:NPN      0:NPN      0:PNP
IB 7.640E-07 1.301E-07 -6.403E-07
IC 1.910E-04 3.253E-05 -3.202E-05
VBE 8.095E-01 7.460E-01 -7.457E-01
VCE 1.491E+00 9.850E+00 -1.015E+01
BETAD 2.500E+02 2.500E+02 5.000E+01
```

```
**** OPERATING POINT INFORMATION THOM= 27.000 TEMP= -35.000
      NODE =VOLTAGE      NODE =VOLTAGE      NODE =VOLTAGE
+0:3      = 8.375E-01 0:4      = 1.806E-01 0:5      =-5.960E-01
+0:6      = 1.206E-01 0:100     = 1.000E+01 0:200     =-1.000E+01
```

```
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT 0:Q2      0:Q3      0:Q4
MODEL 0:NPN      0:NPN      0:PNP
IB 7.650E-07 2.086E-07 -1.027E-06
IC 1.913E-04 5.215E-05 -5.134E-05
VBE 7.766E-01 7.169E-01 -7.166E-01
VCE 1.433E+00 9.879E+00 -1.012E+01
BETAD 2.500E+02 2.500E+02 5.000E+01
```

```
**** OPERATING POINT INFORMATION THOM= 27.000 TEMP= -15.000
      NODE =VOLTAGE      NODE =VOLTAGE      NODE =VOLTAGE
+0:3      = 7.786E-01 0:4      = 1.473E-01 0:5      =-5.960E-01
+0:6      = 9.110E-02 0:100     = 1.000E+01 0:200     =-1.000E+01
```

```
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT 0:Q2      0:Q3      0:Q4
MODEL 0:NPN      0:NPN      0:PNP
IB 7.660E-07 3.116E-07 -1.533E-06
IC 1.915E-04 7.790E-05 -7.667E-05
VBE 7.433E-01 6.875E-01 -6.871E-01
VCE 1.374E+00 9.908E+00 -1.009E+01
BETAD 2.500E+02 2.500E+02 5.000E+01
```

```
**** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 5.000
      NODE =VOLTAGE      NODE =VOLTAGE      NODE =VOLTAGE
+0:3      = 7.189E-01 0:4      = 1.135E-01 0:5      =-5.960E-01
+0:6      = 6.125E-02 0:100     = 1.000E+01 0:200     =-1.000E+01
```

```
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT 0:Q2      0:Q3      0:Q4
MODEL 0:NPN      0:NPN      0:PNP
IB 7.668E-07 4.401E-07 -2.166E-06
IC 1.917E-04 1.100E-04 -1.083E-04
VBE 7.095E-01 6.576E-01 -6.573E-01
VCE 1.314E+00 9.938E+00 -1.006E+01
BETAD 2.500E+02 2.500E+02 5.000E+01
```

```
**** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 25.000
      NODE =VOLTAGE      NODE =VOLTAGE      NODE =VOLTAGE
+0:3      = 6.585E-01 0:4      = 7.939E-02 0:5      =-5.960E-01
+0:6      = 3.107E-02 0:100     = 1.000E+01 0:200     =-1.000E+01
```

```
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT 0:Q2      0:Q3      0:Q4
MODEL 0:NPN      0:NPN      0:PNP
IB 7.675E-07 5.944E-07 -2.925E-06
IC 1.919E-04 1.486E-04 -1.463E-04
VBE 6.754E-01 6.275E-01 -6.271E-01
VCE 1.254E+00 9.968E+00 -1.003E+01
BETAD 2.500E+02 2.500E+02 5.000E+01
```

```
**** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 45.000
      NODE =VOLTAGE      NODE =VOLTAGE      NODE =VOLTAGE
+0:3      = 5.976E-01 0:4      = 4.492E-02 0:5      =-5.960E-01
+0:6      = 5.725E-04 0:100     = 1.000E+01 0:200     =-1.000E+01
```

```
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT 0:Q2      0:Q3      0:Q4
MODEL 0:NPN      0:NPN      0:PNP
IB 7.682E-07 7.741E-07 -3.810E-06
IC 1.920E-04 1.935E-04 -1.905E-04
VBE 6.409E-01 5.970E-01 -5.966E-01
VCE 1.193E+00 9.999E+00 -1.000E+01
BETAD 2.500E+02 2.500E+02 5.000E+01
```

```
**** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 65.000
      NODE =VOLTAGE      NODE =VOLTAGE      NODE =VOLTAGE
+0:3      = 5.360E-01 0:4      = 1.012E-02 0:5      =-5.960E-01
+0:6      =-3.021E-02 0:100     = 1.000E+01 0:200     =-1.000E+01
```

```
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT 0:Q2      0:Q3      0:Q4
MODEL 0:NPN      0:NPN      0:PNP
IB 7.688E-07 9.782E-07 -4.814E-06
IC 1.922E-04 2.446E-04 -2.407E-04
VBE 6.061E-01 5.662E-01 -5.658E-01
VCE 1.132E+00 1.003E+01 -9.969E+00
BETAD 2.500E+02 2.500E+02 5.000E+01
```

```

**** OPERATING POINT INFORMATION      THOM= 27.000 TEMP= 85.000
NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:3      = 4.739E-01 0:4      =-2.498E-02 0:5      =-5.960E-01
+0:6      =-6.127E-02 0:100     = 1.000E+01 0:200     =-1.000E+01

```

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT

```

ELEMENT 0:Q2      0:Q3      0:Q4
MODEL   0:NPN      0:NPN      0:PNP
IB       7.693E-07 1.205E-06 -5.933E-06
IC       1.923E-04 3.014E-04 -2.966E-04
VBE      5.710E-01 5.352E-01 -5.347E-01
VCE      1.069E+00 1.006E+01 -9.938E+00
BETAD    2.500E+02 2.500E+02 5.000E+01

```

```

**** OPERATING POINT INFORMATION      THOM= 27.000 TEMP= 105.000
NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:3      = 4.113E-01 0:4      =-6.037E-02 0:5      =-5.960E-01
+0:6      =-9.259E-02 0:100     = 1.000E+01 0:200     =-1.000E+01

```

**** BIPOLAR JUNCTION TRANSISTORS

SUBCKT

```

ELEMENT 0:Q2      0:Q3      0:Q4
MODEL   0:NPN      0:NPN      0:PNP
IB       7.697E-07 1.454E-06 -7.158E-06
IC       1.924E-04 3.636E-04 -3.579E-04
VBE      5.356E-01 5.039E-01 -5.034E-01
VCE      1.007E+00 1.009E+01 -9.907E+00
BETAD    2.500E+02 2.500E+02 5.000E+01

```

```

**** OPERATING POINT INFORMATION      THOM= 27.000 TEMP= 125.000
NODE      =VOLTAGE      NODE      =VOLTAGE      NODE      =VOLTAGE
+0:3      = 3.482E-01 0:4      =-9.604E-02 0:5      =-5.960E-01
+0:6      =-1.242E-01 0:100     = 1.000E+01 0:200     =-1.000E+01

```

**** BIPOLAR JUNCTION TRANSISTORS

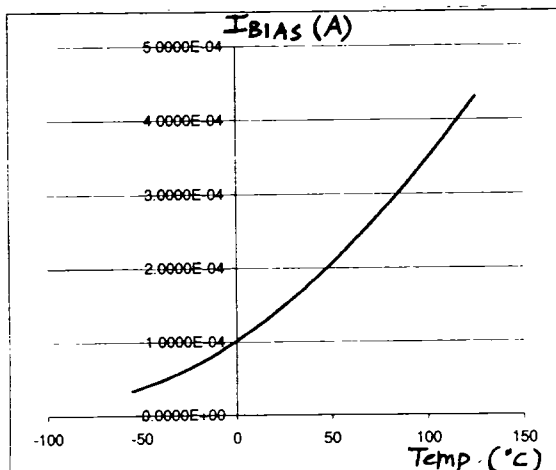
SUBCKT

```

ELEMENT 0:Q2      0:Q3      0:Q4
MODEL   0:NPN      0:NPN      0:PNP
IB       7.699E-07 1.723E-06 -8.480E-06
IC       1.925E-04 4.308E-04 -4.240E-04
VBE      5.000E-01 4.724E-01 -4.718E-01
VCE      9.442E-01 1.012E+01 -9.875E+00
BETAD    2.500E+02 2.500E+02 5.000E+01

```

TEMP (DEG C)	IC3 = IBIAS (A)	TEMP	IC3 = IBIAS (A)
-55	3.253E-05	45	1.935E-04
-35	5.215E-05	65	2.446E-04
-15	7.790E-05	85	3.014E-04
5	1.100E-04	105	3.636E-04
25	1.486E-04	125	4.308E-04



6-28

If the bias current level of 741 input stage is doubled, then from (6.134), $G_{m1} = \frac{1}{2.7 \text{ k}\Omega}$

From (6.138),

$$R_{O1} = R_{out}|_{Q_4} \parallel R_{out}|_{Q_6} = 2 r_{o4} \parallel r_{o6} (1 + g_{m6} (1 \text{ k}\Omega))$$

Using $\eta_{npn} = 2 \times 10^{-4}$, $\eta_{pnp} = 5 \times 10^{-4}$

and $|I_c| = 19.4 \text{ A}$, we have

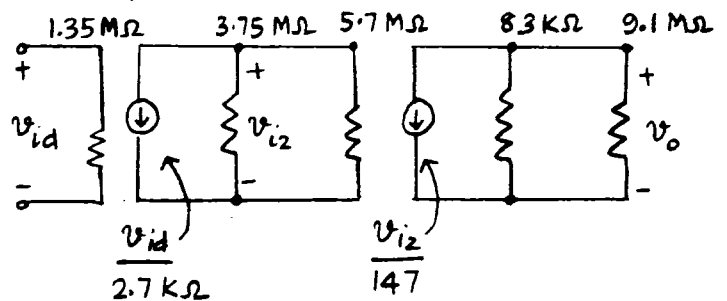
$$r_{o4} = \frac{1}{\eta g_m} = \frac{10^4}{5} \frac{26}{19 \times 10^{-3}} = 2.74 \text{ M}\Omega$$

$$r_{o6} = \frac{10^4}{2} \frac{26}{19 \times 10^{-3}} = 6.84 \text{ M}\Omega$$

$$g_{m6} \times 1 \text{ k}\Omega = 0.73$$

$$\therefore R_{O1} = (5.48) \parallel (6.84 \times 1.73) \text{ M}\Omega = 3.75 \text{ M}\Omega$$

741 equivalent



$$3.75 \parallel 5.7 = 2.26 \text{ M}\Omega ; 83 \text{ k}\Omega \parallel 9.1 \text{ M}\Omega = 82 \text{ k}\Omega$$

$$A_v = \frac{2260}{2.7} \cdot \frac{82}{0.147} = 838 \times 558 = 468,000$$

6.29

If the 100Ω emitter resistor of Q_{17} is removed, then in (6.142) we have,

$$R_{eq1} = r_{\pi17} \pm \frac{\beta}{g_m} = 250 \times \frac{26}{0.55} = 11.8 \text{ k}\Omega$$

$$\begin{aligned} R_{i2} &= r_{\pi16} + (1 + \beta_0)(r_{\pi17} \parallel 50 \text{ k}\Omega) \\ &= 406 \text{ k}\Omega + 251 \times 9.55 \text{ k}\Omega \\ &= 2.8 \text{ M}\Omega \end{aligned}$$

From (6.146)

$$g_{m2} \approx g_{m17} = \frac{0.55}{26} = \frac{1}{47.3 \Omega}$$

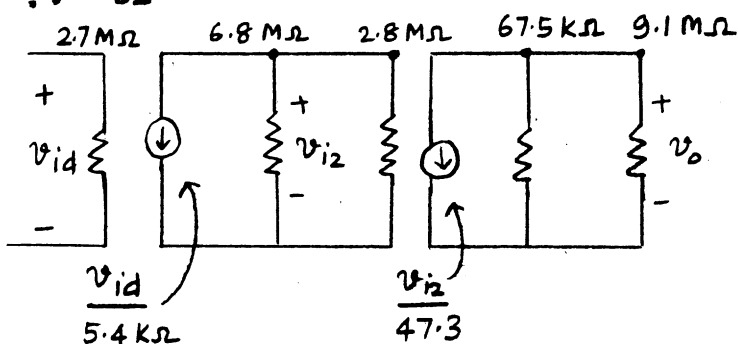
From (6.147)

$$R_{02} = r_{o13p} \parallel r_{o17}$$

$$r_{o13p} = \frac{1}{\eta g_m} = \frac{10^4}{5} \frac{26}{0.55} = 94.5 \text{ k}\Omega$$

$$r_{o17} = \frac{1}{\eta g_m} = \frac{10^4}{2} \frac{26}{0.55} = 236 \text{ k}\Omega$$

$$\therefore R_{02} = 67.5 \text{ k}\Omega$$



$$\begin{aligned} A_v &= \frac{1980}{5.4} \times \frac{67}{0.047} \\ &= 523,000 \end{aligned}$$

6.30

Minimum CM input voltage:

The circuit ceases to function correctly when Q_3 and Q_4 saturate.

Q_3 and Q_4 operate in the F.A.R. when,

$$V_{EC3} > V_{CE(sat)}$$

$$V_{E3} = V_{IC} - V_{BE1}$$

$$V_{C3} = -V_{EE} + V_{BE5} + V_{BE7} + \overbrace{I_{C3}(1\text{K})}^{\text{neglect}}$$

$$V_{EC3} = V_{IC} - V_{BE1} - (-V_{EE}) - V_{BE5} - V_{BE7} > V_{CE(sat)}$$

$$V_{IC} > -V_{EE} + V_{BE1} + V_{BE5} + V_{BE7} + V_{CE(sat)}$$

Maximum CM input voltage:

Q_1 and Q_2 operate in the F.A.R. when

$$V_{CE1} > V_{CE(sat)}$$

$$V_{C1} = V_{CC} - |V_{BE8}|$$

$$V_{E1} = V_{IC} - V_{BE1}$$

$$V_{CE1} = V_{CC} - |V_{BE8}| - V_{IC} + V_{BE1} > V_{CE(sat)}$$

Assume $V_{BE1} = |V_{BE8}|$

$$\text{Then } V_{IC} < V_{CC} - V_{CE(sat)}$$

741 AS A VOLTAGE FOLLOWER

* POWER SUPPLIES

VCC 100 0 15
VBE 200 0 -15

* INPUT STAGE

Q1	7	8	10	NPN
Q2	7	9	11	NPN
Q3	12	6	10	PNP
Q4	16	6	11	PNP
Q5	12	13	14	NPN
Q6	16	13	15	NPN
Q7	100	12	13	NPN
Q8	7	7	100	PNP
Q9	6	7	100	PNP
Q10	6	4	5	NPN
Q11	4	4	200	NPN
Q12	3	3	100	PNP
R1	14	200	1K	
R2	15	200	1K	
R3	13	200	50K	
R5	3	4	39K	
R4	5	200	5K	

* DARLINGTON GAIN STAGE

Q13B	19	3	100	PNP
Q16	100	16	17	NPN
Q17	19	17	18	NPN
R8	18	200	100	
R9	17	200	50K	

* OUTPUT STAGE

Q13A	20	3	100	PNP
Q14	100	20	25	NPN
Q18	20	21	22	NPN
Q19	20	20	21	NPN
Q20	200	22	23	PNP
Q23	200	19	22	PNP
R6	25	9	27	
R7	23	9	22	
R10	21	22	40K	

V11 8 0 0

.MODEL NPN NPN BF=250 IS=5E-15 VAF=130

.MODEL PNP PNP BF=50 IS=2E-15 VAF=50

.MODEL PNPA PNP BF=50 IS=0.5E-15 VAF=50

.MODEL PNFB PNP BF=50 IS=1.5E-15 VAF=50

.OPTIONS NOPAGE NOMOD

.WIDTH OUT=80

.OP

.DC V11 -15 15 0.5

* ASSUMING $V_{CE}(\text{SAT}) = 0.2 \text{ V}$ AND $V_{BE}(\text{ON}) = 0.7 \text{ V}$,
* THE HAND CALCULATIONS PREDICT A COMMON-MODE RANGE OF
* $-12.7 \text{ V} < V_{IC} < 14.8 \text{ V}$
* IN THE VOLTAGE-FOLLOWER CONFIGURATION, $V_O = V_I = V_{IC}$
* AS LONG AS THE AMPLIFIER IS WORKING CORRECTLY.
* THE RESULTS OF THIS SIMULATION SHOW THAT
* $V_O = V_I$ FOR THE FOLLOWING RANGE:
* $-13 \text{ V} < V_I < 14.5 \text{ V}$
* THEREFORE, THIS SIMULATION SHOWS THAT THE
* COMMON MODE INPUT RANGE IS:
* $-13 \text{ V} < (V_O = V_I = V_{IC}) < 14.5 \text{ V}$
* WHICH IS CLOSE TO THE RESULT
* PREDICTED BY HAND CALCULATIONS.

.PLOT DC V(9)

.END

***** DC TRANSFER CURVES TNOM= 27.000 TEMP= 27.000

VOLT	V(9)								
(A)		-2.000E+01	-1.000E+01	0.	1.000E+01	2.000E+01			
-1.500E+01	-1.31E+01	+	-A	+	+	+	+	+	+
-1.450E+01	-1.31E+01	+	A	+	+	+	+	+	+
-1.400E+01	-1.31E+01	+	A	+	+	+	+	+	+
-1.350E+01	-1.31E+01	+	A	+	+	+	+	+	+
-1.300E+01	-1.30E+01	+	A	+	+	+	+	+	+
-1.250E+01	-1.25E+01	+	A	+	+	+	+	+	+
-1.200E+01	-1.20E+01	+	A	+	+	+	+	+	+
-1.150E+01	-1.15E+01	+	A	+	+	+	+	+	+
-1.100E+01	-1.10E+01	+	A	+	+	+	+	+	+
-1.050E+01	-1.05E+01	+	A	+	+	+	+	+	+
-1.000E+01	-9.99E+00	+	-A	+	+	+	+	+	+
-9.500E+00	-9.50E+00	+	A	+	+	+	+	+	+
-9.000E+00	-9.00E+00	+	A	+	+	+	+	+	+
-8.500E+00	-8.50E+00	+	A	+	+	+	+	+	+
-8.000E+00	-8.00E+00	+	A	+	+	+	+	+	+
-7.500E+00	-7.50E+00	+	A	+	+	+	+	+	+
-7.000E+00	-7.00E+00	+	A	+	+	+	+	+	+
-6.500E+00	-6.50E+00	+	A	+	+	+	+	+	+
-6.000E+00	-6.00E+00	+	A	+	+	+	+	+	+
-5.500E+00	-5.50E+00	+	A	+	+	+	+	+	+
-5.000E+00	-5.00E+00	+	-A	+	+	+	+	+	+
-4.500E+00	-4.50E+00	+	A	+	+	+	+	+	+
-4.000E+00	-4.00E+00	+	A	+	+	+	+	+	+
-3.500E+00	-3.50E+00	+	A	+	+	+	+	+	+
-3.000E+00	-3.00E+00	+	A	+	+	+	+	+	+
-2.500E+00	-2.50E+00	+	A	+	+	+	+	+	+
-2.000E+00	-2.00E+00	+	A	+	+	+	+	+	+
-1.500E+00	-1.50E+00	+	A	+	+	+	+	+	+
-1.000E+00	-1.00E+00	+	A	+	+	+	+	+	+
-5.000E-01	-5.00E-01	+	A	+	+	+	+	+	+
0.	2.74E-04	+	-A	+	+	+	+	+	+
5.000E-01	5.00E-01	+	A	+	+	+	+	+	+
1.000E+00	1.00E+00	+	A	+	+	+	+	+	+
1.500E+00	1.50E+00	+	A	+	+	+	+	+	+
2.000E+00	2.00E+00	+	A	+	+	+	+	+	+
2.500E+00	2.50E+00	+	A	+	+	+	+	+	+
3.000E+00	3.00E+00	+	A	+	+	+	+	+	+
3.500E+00	3.50E+00	+	A	+	+	+	+	+	+
4.000E+00	4.00E+00	+	A	+	+	+	+	+	+
4.500E+00	4.50E+00	+	A	+	+	+	+	+	+
5.000E+00	5.00E+00	+	-A	+	+	+	+	+	+
5.500E+00	5.50E+00	+	A	+	+	+	+	+	+
6.000E+00	6.00E+00	+	A	+	+	+	+	+	+
6.500E+00	6.50E+00	+	A	+	+	+	+	+	+
7.000E+00	7.00E+00	+	A	+	+	+	+	+	+
7.500E+00	7.50E+00	+	A	+	+	+	+	+	+
8.000E+00	8.00E+00	+	A	+	+	+	+	+	+
8.500E+00	8.50E+00	+	A	+	+	+	+	+	+
9.000E+00	9.00E+00	+	A	+	+	+	+	+	+
9.500E+00	9.50E+00	+	A	+	+	+	+	+	+
1.000E+01	1.00E+01	+	-A	+	+	+	+	+	+
1.050E+01	1.05E+01	+	A	+	+	+	+	+	+
1.100E+01	1.10E+01	+	A	+	+	+	+	+	+
1.150E+01	1.15E+01	+	A	+	+	+	+	+	+
1.200E+01	1.20E+01	+	A	+	+	+	+	+	+
1.250E+01	1.25E+01	+	A	+	+	+	+	+	+
1.300E+01	1.30E+01	+	A	+	+	+	+	+	+
1.350E+01	1.35E+01	+	A	+	+	+	+	+	+
1.400E+01	1.40E+01	+	A	+	+	+	+	+	+
1.450E+01	1.45E+01	+	A	+	+	+	+	+	+
1.500E+01	1.46E+01	+	-A	+	+	+	+	+	+

**** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:3	= 1.431E+01 0:4		= -1.433E+01 0:5		= -1.490E+01
+0:6	= -1.107E+00 0:7		= 1.441E+01 0:8		= 0.
+0:9	= 2.744E-04 0:10		= -5.439E-01 0:11		= -5.437E-01
+0:12	= -1.389E+01 0:13		= -1.444E+01 0:14		= -1.499E+01
+0:15	= -1.499E+01 0:16		= -1.370E+01 0:17		= -1.426E+01
+0:18	= -1.493E+01 0:19		= -1.260E+00 0:20		= 5.904E-01
+0:21	= 2.345E-02 0:22		= -6.088E-01 0:23		= -2.361E-03
+0:25	= 3.509E-03 0:100		= 1.500E+01 0:200		= -1.500E+01

6.31

First consider the bipolar differential pair with tail current source and resistive loads by itself. Let V_{os1} represent the offset of that circuit referred to the input of that circuit (the bases of Q_1 and Q_2)

From (6.164),

$$V_{os1} = V_T \left(-\frac{\Delta I_S}{I_S} - \frac{\Delta R}{R} \right)$$

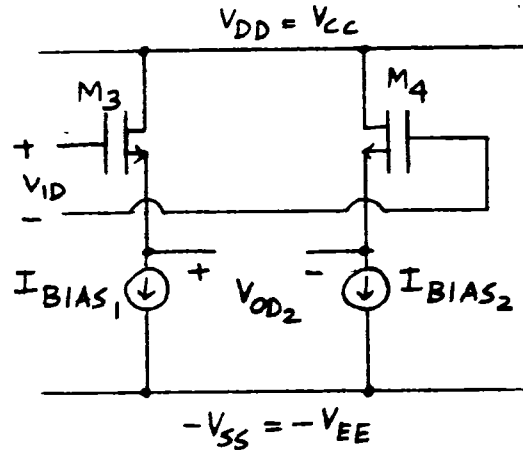
$$\text{where } I_S = \frac{I_{S1} + I_{S2}}{2}$$

$$\Delta I_S = I_{S1} - I_{S2}$$

$$R = \frac{R_1 + R_2}{2}$$

$$\Delta R = R_1 - R_2$$

Second, consider the MOS source followers by themselves. Let V_{os2} represent the offset of the source followers only referred to the input of the entire circuit (the gates of M_3 and M_4)



$$V_{OD2} = V_{ID} - (V_{GS3} - V_{GS4})$$

$$V_{ID} = V_{OD2} + V_{GS3} - V_{GS4}$$

$$V_{os2} = V_{ID} \text{ for which } V_{OD2} = 0$$

$$V_{os2} = V_{GS3} - V_{GS4}$$

$$V_{GS3} = V_{t3} - V_{OV3}$$

$$V_{GS4} = V_{t4} - V_{OV4}$$

$$V_{OV3} = \sqrt{\frac{2 I_{BIAS1}}{K' \left(\frac{W}{L} \right)_3}}$$

$$V_{OV4} = \sqrt{\frac{2 I_{BIAS2}}{K' \left(\frac{W}{L} \right)_4}}$$

$$V_{os2} = V_{t3} - V_{t4} + \sqrt{\frac{2 I_{BIAS1}}{K' \left(\frac{W}{L} \right)_3}} - \sqrt{\frac{2 I_{BIAS2}}{K' \left(\frac{W}{L} \right)_4}}$$

$$\text{Let } I_{BIAS} = \frac{I_{BIAS1} + I_{BIAS2}}{2}$$

$$\Delta I_{BIAS} = I_{BIAS1} - I_{BIAS2}$$

$$\therefore I_{BIAS1} = I_{BIAS} + \frac{\Delta I_{BIAS}}{2}$$

$$I_{BIAS2} = I_{BIAS} - \frac{\Delta I_{BIAS}}{2}$$

$$\text{Also, } \left(\frac{W}{L}\right)_3 = \left(\frac{W}{L}\right) + \frac{1}{2} \Delta\left(\frac{W}{L}\right)$$

$$\left(\frac{W}{L}\right)_4 = \left(\frac{W}{L}\right) - \frac{1}{2} \Delta\left(\frac{W}{L}\right)$$

$$\text{Where, } \left(\frac{W}{L}\right) = \frac{\left(\frac{W}{L}\right)_3 + \left(\frac{W}{L}\right)_4}{2}$$

$$\Delta\left(\frac{W}{L}\right) = \left(\frac{W}{L}\right)_3 - \left(\frac{W}{L}\right)_4$$

$$\text{Finally, } \Delta V_t = V_{t3} - V_{t4}$$

$$V_{os2} = \Delta V_t + \sqrt{\frac{2(I_{BIAS})(1 + \frac{\Delta I_{BIAS}}{2I_{BIAS}})}{k'(\frac{W}{L}) \left[1 + \frac{\Delta(W/L)}{2(W/L)}\right]}} - \sqrt{\frac{2(I_{BIAS})(1 - \frac{\Delta I_{BIAS}}{2I_{BIAS}})}{k'(\frac{W}{L}) \left[1 - \frac{\Delta(W/L)}{2(W/L)}\right]}}$$

$$\text{Let } V_{OV} = \sqrt{\frac{2I_{BIAS}}{k' W/L}}$$

$$V_{os2} = \Delta V_t + V_{OV} \left[\sqrt{\frac{1 + \frac{\Delta I_{BIAS}}{2I_{BIAS}}}{1 + \frac{\Delta(W/L)}{2(W/L)}}} - \sqrt{\frac{1 - \frac{\Delta I_{BIAS}}{2I_{BIAS}}}{1 - \frac{\Delta(W/L)}{2(W/L)}}} \right]$$

$$\text{Since } \sqrt{x} \approx 1 + \frac{x}{2} \text{ for } x \approx 1$$

$$V_{os2} \approx \Delta V_t + \frac{V_{OV}}{2} \left[\frac{1 + \frac{\Delta I_{BIAS}}{2I_{BIAS}}}{1 + \frac{\Delta(W/L)}{2(W/L)}} - \frac{1 - \frac{\Delta I_{BIAS}}{2I_{BIAS}}}{1 - \frac{\Delta(W/L)}{2(W/L)}} \right]$$

$$\text{since } \frac{1}{1+y} \approx 1-y \text{ for } y \ll 1,$$

$$V_{os2} \approx \Delta V_t + \frac{V_{OV}}{2} \left[1 + \frac{\Delta I_{BIAS}}{2I_{BIAS}} - \frac{\Delta(W/L)}{2(W/L)} - \left(1 - \frac{\Delta I_{BIAS}}{2I_{BIAS}} + \frac{\Delta(W/L)}{2(W/L)} \right) \right]$$

$$V_{os2} \approx \Delta V_t + \frac{V_{OV}}{2} \left[\frac{\Delta I_{BIAS}}{I_{BIAS}} - \frac{\Delta(W/L)}{(W/L)} \right]$$

Let V_{OS} represent the total offset including both V_{OS1} and V_{OS2} .

$$V_{OS} = \frac{V_{OS1}}{\text{source-follower gain}} + V_{OS2}$$

Since the source-follower gain ≈ 1 ,

$$V_{OS} \approx V_T \left(-\frac{\Delta I_S}{I_S} - \frac{\Delta R}{R} \right) + \Delta V_t + \frac{V_{OV}}{2} \left[\frac{\Delta I_{BIAS}}{I_{BIAS}} - \frac{\Delta(W/L)}{W/L} \right]$$

CHAPTER 7

7.1

(a) Transistor parameters are

$$r_{\pi} = \frac{\beta_o}{g_m} = 200 \times 52 = 10.4 \text{ k}\Omega$$

$$\tau_T = \frac{1}{2\pi f_T} = 318 \text{ ps}$$

$$C_{\pi} + C_{\mu} = g_m \tau_T = \frac{1}{52} \times 318 = 6.12 \text{ pF}$$

$$\therefore C_{\pi} = 6.1 - 0.3 = 5.8 \text{ pF}$$

$$\begin{aligned} C_M &= (1 + g_m R_L) C_{\mu} \\ &= \left(1 + \frac{3000}{52}\right) \times 0.3 = 17.6 \text{ pF} \end{aligned}$$

In (7.12) and (7.9)

$$\begin{aligned} f_{-3\text{dB}} &= \frac{1}{2\pi} \frac{5000 + 300 + 10400}{(5000 + 300) \times 10400} \frac{10^{12}}{5.8 + 17.6} \text{ Hz} \\ &= 1.94 \text{ MHz} \end{aligned}$$

(b) From (7.27)

$$P_2 = -\left(\frac{1}{R_L C_{\mu}} + \frac{1}{R C_{\pi}} + \frac{1}{R_L C_{\pi}} + \omega_T\right)$$

$$R = (R_S + r_b) \parallel r_{\pi}$$

$$= 5300 \parallel 10400 = 3511 \Omega$$

$$\begin{aligned} \therefore P_2 &= -\left(\frac{10^{12}}{3000 \times 0.3} + \frac{10^{12}}{3511 \times 5.8} + \frac{10^{12}}{3000 \times 5.8} \right. \\ &\quad \left. + 2\pi \times 500 \times 10^6\right) \\ &= -(11.1 + 0.49 + 0.57 + 31.4) \times 10^8 \text{ rad/sec} \\ &= -43.6 \times 10^8 \text{ rad/sec} \\ &= -693 \text{ MHz} \end{aligned}$$

7-2

COMMON EMITTER GAIN STAGE

VCC 1 0 5V
 RL 1 2 3K
 Q1 2 3 0 NPN
 RS 4 3 5K
 VI 4 0 0.7696 AC
 .TF V(2) VI
 .PLOT AC VDB(2)
 .PLOT AC VP(2)
 .AC DEC 10 100K 1GIG
 .MODEL NPN NPN IS=1E-16A BF=200
 + RB=300 CJC=0.3PF CJS=0 TF=302PS
 * ASSUME CJE SMALL COMPARED TO CB
 .OPTIONS NOPAGE NOMOD
 .WIDTH OUT=80
 .OPTIONS SPICE
 .OP
 .END

***** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

+0:1 = 5.000E+00 0:2 = 3.497E+00 0:3 = 7.571E-01
 +0:4 = 7.696E-01

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT 0:Q1
 MODEL 0:NPN
 IB 2.504E-06
 IC 5.009E-04
 VBE 7.571E-01
 VCE 3.497E+00
 VBC -2.740E+00
 VS -3.497E+00
 POWER 1.754E-03
 BETAD 2.000E+02
 GM 1.937E-02
 RPI 1.032E+04
 RI 3.000E+02
 RO 2.741E+16
 CPI 5.849E-12
 CMU 1.806E-13
 CBX 0.
 CCS 0.
 BETAAC 2.000E+02
 FT 5.112E+08

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(2)/VI = -3.839E+01
 INPUT RESISTANCE AT VI = 1.562E+04
 OUTPUT RESISTANCE AT V(2) = 3.000E+03

***** AC ANALYSIS

TNOM= 27.000 TEMP= 27.000

FREQ	VDB(2)					
(A)		-4.000E+01	-2.000E+01	0.	2.000E+01	4.000E+01
1.000E+05	3.16E+01					
1.258E+05	3.16E+01					
1.584E+05	3.16E+01					
1.995E+05	3.16E+01					
2.511E+05	3.16E+01					
3.162E+05	3.16E+01					
3.981E+05	3.15E+01					
5.011E+05	3.15E+01					
6.309E+05	3.14E+01					
7.943E+05	3.13E+01					
1.000E+06	3.11E+01					
1.258E+06	3.08E+01					
1.584E+06	3.04E+01					
1.995E+06	2.99E+01					
2.511E+06	2.90E+01					
3.162E+06	2.80E+01					
3.981E+06	2.67E+01					
5.011E+06	2.52E+01					
6.309E+06	2.36E+01					
7.943E+06	2.19E+01					
1.000E+07	2.01E+01					
1.258E+07	1.82E+01					
1.584E+07	1.62E+01					
1.995E+07	1.43E+01					
2.511E+07	1.23E+01					
3.162E+07	1.03E+01					
3.981E+07	8.39E+00					
5.011E+07	6.39E+00					
6.309E+07	4.38E+00					
7.943E+07	2.37E+00					
1.000E+08	3.56E-01					
1.258E+08	-1.67E+00					
1.584E+08	-3.73E+00					
1.995E+08	-5.82E+00					
2.511E+08	-7.95E+00					
3.162E+08	-1.01E+01					
3.981E+08	-1.24E+01					
5.011E+08	-1.49E+01					
6.309E+08	-1.75E+01					
7.943E+08	-2.03E+01					
1.000E+09	-2.34E+01					

FREQ	VP(2)				
(A)		5.000E+01	1.000E+02	1.500E+02	2.000E+02
1.000E+05	1.77E+02				
1.258E+05	1.77E+02				
1.584E+05	1.76E+02				
1.995E+05	1.75E+02				
2.511E+05	1.74E+02				
3.162E+05	1.73E+02				
3.981E+05	1.71E+02				
5.011E+05	1.69E+02				
6.309E+05	1.67E+02				
7.943E+05	1.63E+02				
1.000E+06	1.59E+02				
1.258E+06	1.55E+02				
1.584E+06	1.49E+02				
1.995E+06	1.43E+02				
2.511E+06	1.37E+02				
3.162E+06	1.30E+02				
3.981E+06	1.24E+02				
5.011E+06	1.18E+02				
6.309E+06	1.13E+02				
7.943E+06	1.08E+02				
1.000E+07	1.04E+02				
1.258E+07	1.01E+02				
1.584E+07	9.86E+01				
1.995E+07	9.63E+01				
2.511E+07	9.44E+01				
3.162E+07	9.26E+01				
3.981E+07	9.10E+01				
5.011E+07	8.95E+01				
6.309E+07	8.79E+01				
7.943E+07	8.62E+01				
1.000E+08	8.44E+01				
1.258E+08	8.22E+01				
1.584E+08	7.97E+01				
1.995E+08	7.66E+01				
2.511E+08	7.30E+01				
3.162E+08	6.86E+01				
3.981E+08	6.35E+01				
5.011E+08	5.76E+01				
6.309E+08	5.10E+01				
7.943E+08	4.39E+01				
1.000E+09	3.56E+01				

$$g_m = \sqrt{2k_n' \frac{W}{L} I_D} = \sqrt{2 \times 60 \times 10^{-6} \times \frac{100}{2 - 2 \times 0.2 - 0} \times 500 \times 10^{-6}}$$

$$= 1.9 \times 10^{-3} \text{ A/V}$$

$$A_v = -g_m R_L = -1.9 \times 10^{-3} \times 5 \times 10^3 = -9.5$$

$$C_{gs} = \frac{2}{3} W L_{eff} C_{ox} + W L_d C_{ox}$$

$$= \frac{2}{3} 100 \times 1.6 \times 0.7 + 100 \times 0.2 \times 0.7$$

$$= 89 \text{ fF}$$

$$C_{gd} = W L_d C_{ox} = 100 \times 0.2 \times 0.7 = 14 \text{ fF}$$

(a) Use the Miller effect.

$$|P_1| = \frac{1}{R_s [C_{gs} + C_{gd}(1 - A_v)]}$$

$$= \frac{1}{10k [89 + 14(1 + 9.5)] \times 10^{-15}}$$

$$= \frac{1}{2.4 \times 10^{-9}} = 4.2 \times 10^8 \text{ rad/s}$$

$$f_{-3dB} = \frac{|P_1|}{2\pi} = 67 \text{ MHz}$$

(b) Do not use the Miller effect to calculate the second pole.

From Eq. (7.26),

$$|P_2| = \frac{1}{|A_1| R_L R_s C_{gd} C_{gs}}$$

$$= \frac{1}{4.2 \times 10^8 \times 5k \times 10k \times 14 \text{ fF} \times 89 \text{ fF}}$$

$$= 3.8 \times 10^{10} \text{ rad/s}$$

It is equivalent to 6.1 GHz.

COMMON SOURCE AMPLIFIER

```

VDD 1 0 5
VI 2 0 DC 1.216 AC 1
RS 2 3 10K
RL 1 4 5K
M1 4 3 0 0 CMOSN W=100U L=2U
* COX'=0.7FF/UM**2=BOX/TOX => TOX=500 ANGSTROMS
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0 VTO=0.7 KP=60U LD=0.2U TOX=500E-10
.OPTIONS NOMOD
.AC DEC 10 1MEG 10G
.PLOT AC VM(4)
.WIDTH OUT=80
.OPTIONS SPICE
.END

```

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

```

+0:1 = 5.000E+00 0:2 = 1.216E+00 0:3 = 1.216E+00
+0:4 = 2.503E+00

```

**** MOSFETS

```

SUBCKT
ELEMENT 0:M1
MODEL 0:CMOSN
ID 4.992E-04
IBS 0.
IRD -2.504E-14
VGS 1.216E+00
VDS 2.503E+00
VBS 0.
VTH 7.000E-01
VDSAT 5.160E-01
BETA 3.750E-03
GAM KFF 0.
GM 1.935E-03
GDS 0.
GMB 0.
COTOT 1.418E-14
COGOT 1.050E-13
CSTOT 8.748E-14
CBTOT 3.349E-15
CGS 8.748E-14
CGD 1.418E-14

```

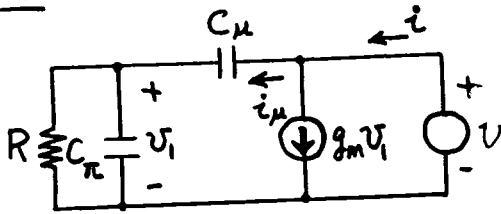
***** AC ANALYSIS

THOM= 27.000 TEMP= 27.000

FREQ	VM(4)					
(A)		1.000E-02	1.000E-01	1.000E+00	9.999E+00	9.999E+01
1.000E+06	9.67E+00					
1.258E+06	9.67E+00	+	+	+	A	+
1.584E+06	9.67E+00	+	+	+	+	A
1.995E+06	9.67E+00	+	+	+	+	A
2.511E+06	9.66E+00	+	+	+	+	A
3.162E+06	9.66E+00	+	+	+	+	A
3.981E+06	9.65E+00	+	+	+	+	A
5.011E+06	9.64E+00	+	+	+	+	A
6.309E+06	9.62E+00	+	+	+	+	A
7.943E+06	9.60E+00	+	+	+	+	A
1.000E+07	9.56E+00					
1.258E+07	9.49E+00	+	+	+	+	A
1.584E+07	9.39E+00	+	+	+	+	A
1.995E+07	9.24E+00	+	+	+	+	A
2.511E+07	9.01E+00	+	+	+	+	A
3.162E+07	8.68E+00	+	+	+	+	A
3.981E+07	8.23E+00	+	+	+	+	A
5.011E+07	7.64E+00	+	+	+	+	A
6.309E+07	6.91E+00	+	+	+	+	A
7.943E+07	6.09E+00	+	+	+	+	A
1.000E+08	5.24E+00					
1.258E+08	4.41E+00	+	+	+	+	A
1.584E+08	3.64E+00	+	+	+	+	A
1.995E+08	2.97E+00	+	+	+	+	A
2.511E+08	2.40E+00	+	+	+	+	A
3.162E+08	1.93E+00	+	+	+	+	A
3.981E+08	1.54E+00	+	+	+	+	A
5.011E+08	1.23E+00	+	+	+	+	A
6.309E+08	9.79E-01	+	+	+	+	A
7.943E+08	7.77E-01	+	+	+	+	A
1.000E+09	6.15E-01					
1.258E+09	4.86E-01	+	+	+	+	A
1.584E+09	3.82E-01	+	+	+	+	A
1.995E+09	2.98E-01	+	+	+	+	A
2.511E+09	2.31E-01	+	+	+	+	A
3.162E+09	1.77E-01	+	+	+	+	A
3.981E+09	1.33E-01	+	+	+	+	A
5.011E+09	9.87E-02	+	+	+	+	A
6.309E+09	7.16E-02	+	+	+	+	A
7.943E+09	5.09E-02	+	+	+	+	A
1.000E+10	3.58E-02					

7-4

7.3



$$R = (R_s + r_b) \parallel r_{\pi}$$

$$V_1 = \frac{Z_{\pi}}{Z_{\pi} + \frac{1}{C_{\pi} s}} V, \text{ where } Z_{\pi} = \frac{R}{1 + RC_{\pi} s}$$

$$g_m V_1 = g_m \frac{R V}{R + (1 + RC_{\pi} s) \frac{1}{C_{\mu} s}}$$

$$= \frac{g_m R C_{\mu} s}{1 + RC_{\pi} s + RC_{\mu} s} V$$

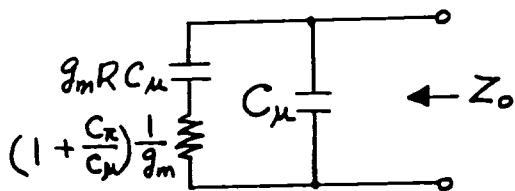
$$i = i_{\mu} + g_m V_1$$

$$\therefore \frac{1}{Z_o} = \frac{i}{V} = \frac{i_{\mu}}{V} + \frac{g_m V_1}{V}$$

$$= \frac{i_{\mu}}{V} + \frac{g_m R C_{\mu} s}{1 + RC_{\pi} s + RC_{\mu} s}$$

But $\frac{i_{\mu}}{V} \approx C_{\mu} s$, because $C_{\pi} \gg C_{\mu}$

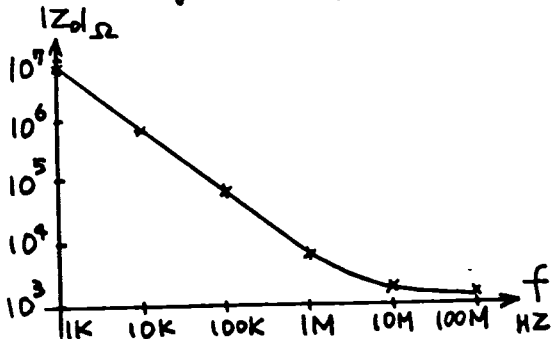
$$\therefore Z_o \approx \frac{1}{C_{\mu} s} \parallel \left(\frac{1}{g_m R C_{\mu} s} + \frac{C_{\pi}}{C_{\mu}} \frac{1}{g_m} + \frac{1}{g_m} \right)$$



$$C_{\mu} = 0.3 \text{ pF}$$

$$g_m R C_{\mu} = \frac{3511}{52} \times 0.3 = 20.3 \text{ pF}$$

$$\left(1 + \frac{C_{\pi}}{C_{\mu}}\right) \frac{1}{g_m} = \left(1 + \frac{5.8}{0.3}\right) 52 = 1057 \Omega$$



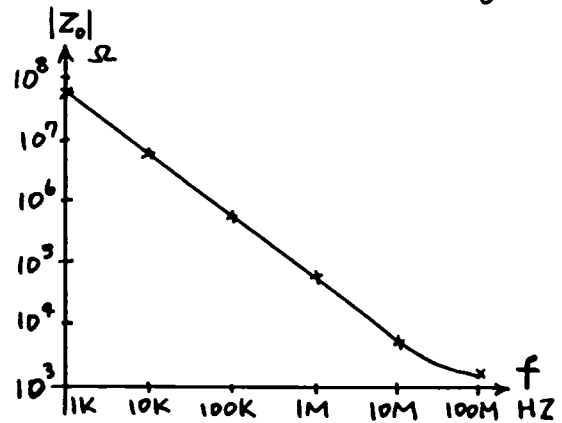
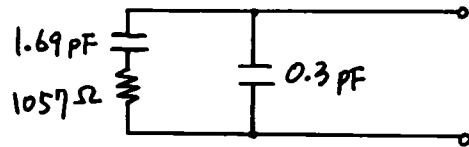
7.4

$$R_s = 0, C_{\mu} = 0.3 \text{ pF}$$

$$R = r_b \parallel r_{\pi} = 300 \parallel 10400 = 292 \Omega$$

$$g_m R C_{\mu} = \frac{292}{52} \times 0.3 = 1.69 \text{ pF}$$

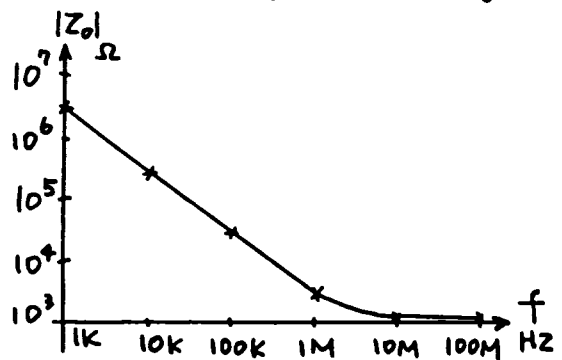
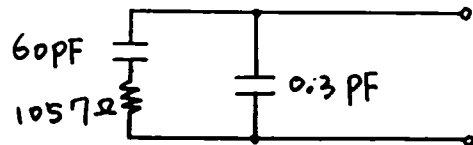
$$\left(1 + \frac{C_{\pi}}{C_{\mu}}\right) \frac{1}{g_m} = 1057 \Omega$$



$$R_s = \infty, C_{\mu} = 0.3 \text{ pF}$$

$$R = r_{\pi} = 10400 \Omega$$

$$g_m R C_{\mu} = \frac{10400}{52} \times 0.3 = 60 \text{ pF}$$



7-5

7.5

$$C_{gs} = \frac{2}{3} W L_{eff} C_{ox} + W L_d C_{ox}$$

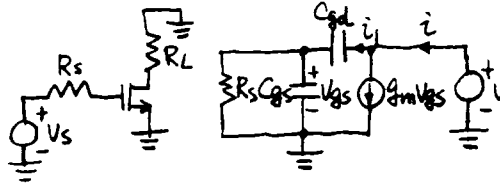
$$= \frac{2}{3} 100(2 - 2 \times 0.2 - 0) \times 0.7 + 100 \times 0.2 \times 0.7$$

$$= 89 \text{ fF}$$

$$C_{gd} = W L_d C_{ox} = 100 \times 0.2 \times 0.7 = 14 \text{ fF}$$

$$g_m = \sqrt{2 k_n' \frac{W}{L_{eff}} I_D} = \sqrt{2 \times 60 \times 10^{-6} \frac{100}{2-0.4-0} \times 0.5 \times 10^{-3}}$$

$$= 1.9 \times 10^{-3} \text{ A/V} = 1.9 \text{ mA/V}$$



$$R_s \parallel \frac{1}{s C_{gs}} = \frac{R_s}{1 + s R_s C_{gs}}$$

$$V_{gs} = V \frac{\frac{R_s}{1 + s R_s C_{gs}}}{\frac{1}{s C_{gd}} + \frac{R_s}{1 + s R_s C_{gs}}} = V \frac{R_s}{R_s + \frac{1 + s R_s C_{gs}}{s C_{gd}}}$$

$$\therefore C_{gd} \ll C_{gs} \text{ and } \frac{1}{s C_{gd}} \gg R_s \parallel \frac{1}{s C_{gs}}$$

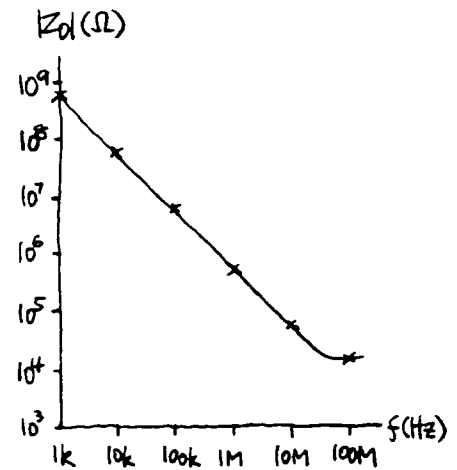
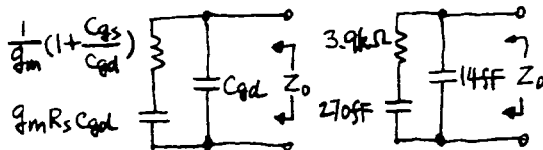
$$\therefore i_1 \approx s C_{gd} V$$

$$\frac{1}{Z_o} = \frac{i}{V} = \frac{i_1}{V} + \frac{g_m V_{gs}}{V} = s C_{gd} + \frac{g_m R_s}{R_s + \frac{1 + s R_s C_{gs}}{s C_{gd}}}$$

$$Z_o = \frac{1}{s C_{gd} \parallel \left[\frac{1}{g_m} \left(1 + \frac{C_{gs}}{C_{gd}} \right) + \frac{1}{s g_m R_s C_{gd}} \right]}$$

$$\frac{1}{g_m} \left(1 + \frac{C_{gs}}{C_{gd}} \right) = \frac{1}{1.9 \times 10^{-3}} \left(1 + \frac{89}{14} \right) = 3.9 \times 10^3 \Omega$$

$$g_m R_s C_{gd} = 1.9 \times 10^{-3} \times 10 \times 10^3 \times 14 = 270 \text{ fF}$$



7-6

7.6

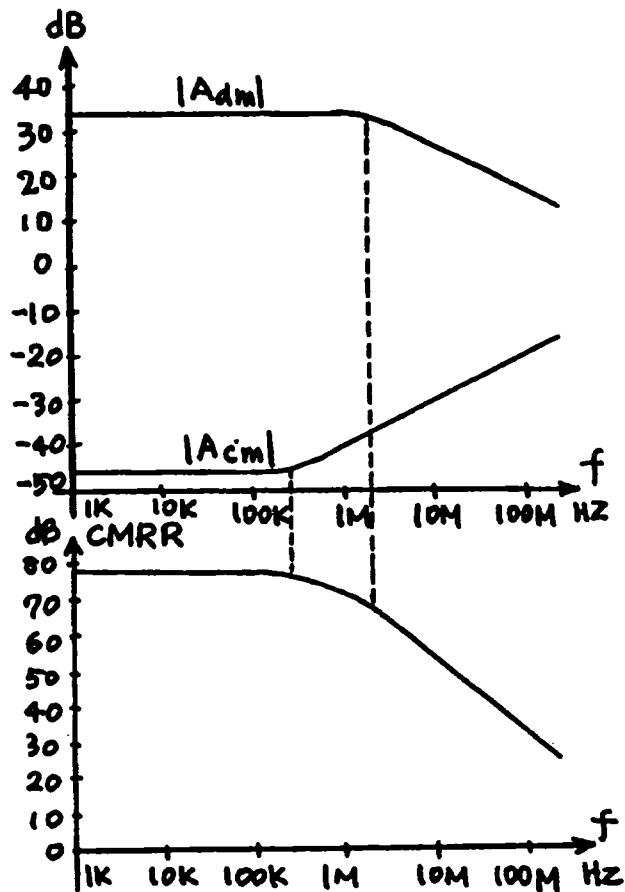
$$\begin{aligned} A_{cm} &= -\frac{R_L}{2R_T} (1 + j\omega C_T R_T) \\ &= -\frac{3}{600} (1 + j\omega 300 \times 10^3 \times 2 \times 10^{-12}) \\ &= -5 \times 10^{-3} (1 + j\omega \times 600 \times 10^{-9}) \end{aligned}$$

Using dominant pole

$$\begin{aligned} A_{dm} &= -g_m R_L \frac{r_{\pi}}{R_s + r_b + r_{\pi}} \frac{1}{1 + j\frac{\omega}{\omega_1}} \\ &= -\frac{3000}{52} \frac{10.4k}{10.4k + 300 + 5k} \frac{1}{1 + j\frac{f}{1.94 \times 10^6}} \\ &= -\frac{38.2}{1 + j\frac{f}{1.94 \times 10^6}} \end{aligned}$$

$$A_{cm} = -0.005 (1 + j\frac{f}{265 \times 10^3})$$

$$CMRR = \left| \frac{A_{dm}}{A_{cm}} \right|$$



DIFFERENTIAL AMP, COMMON MODE

```

VCC 1 0 5V
VEE 9 0 -5V
IEE 7 9 1MA
REE 7 9 300K
CEE 7 9 2PF
RL1 1 2 3K
RL2 1 8 3K
Q1 2 3 7 NPN
RS1 4 3 5K
Q2 8 6 7 NPN
RS2 5 6 5K
VIC 4 0 0V AC
EVIC 5 0 4 0 1
.TF V(2) VIC
.PLOT AC VDB(2)
.AC DEC 10 10K 20MEG
.MODEL NPN NPN IS=1E-16A BF=200
+ RB=300 CJC=0.3PF CJS=0 TF=302PS
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

```

***** OPERATING POINT INFORMATION      TNOM= 27.000 TEMP= 27.000
+D:1      = 5.000E+00 0:2      = 3.486E+00 0:3      = -1.261E-02
+O:4      = 0.          0:5      = 0.          0:6      = -1.261E-02
+O:7      = -7.699E-01 0:8      = 3.486E+00 0:9      = -5.000E+00

```

**** BIPOLAR JUNCTION TRANSISTORS

```

ELEMENT 0:Q1      0:Q2
MODEL    0:NPN     0:NPN
IB       2.523E-06 2.523E-06
IC       5.045E-04 5.045E-04
VBE     7.573E-01 7.573E-01
VCE     4.256E+00 4.256E+00
VBC     -3.499E+00 -3.499E+00
VS       -3.486E+00 -3.486E+00
POWER    2.149E-03 2.149E-03
BETAD    2.000E+02 2.000E+02
GM       1.951E-02 1.951E-02
RPI      1.025E+04 1.025E+04
RX       3.000E+02 3.000E+02
RO       3.499E+16 3.499E+16
CPI      5.891E-12 5.891E-12
CHU      1.693E-13 1.693E-13
CBX       0.        0.
CCS       0.        0.
BETAC    2.000E+02 2.000E+02
FT       5.122E+08 5.122E+08

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(2)/VIC      = -4.974E-03
INPUT RESISTANCE AT VIC      = 1.206E+08
OUTPUT RESISTANCE AT V(2)    = 3.000E+03

```

***** AC ANALYSIS

TNOM= 27.000 TEMP= 27.000

FREQ	VDB(2)	-4.000E+01	-2.000E+01	0.	2.000E+01
9.999E+03	-4.60E+01	A			
1.258E+04	-4.60E+01	A			
1.584E+04	-4.60E+01	A			
1.995E+04	-4.60E+01	A			
2.511E+04	-4.60E+01	A			
3.162E+04	-4.60E+01	A			
3.981E+04	-4.60E+01	A			
5.011E+04	-4.59E+01	A			
6.309E+04	-4.59E+01	A			
7.943E+04	-4.58E+01	A			
1.000E+05	-4.56E+01	A			
1.258E+05	-4.54E+01	A			
1.584E+05	-4.51E+01	A			
1.995E+05	-4.46E+01	A			
2.511E+05	-4.39E+01	A			
3.162E+05	-4.31E+01	A			
3.981E+05	-4.22E+01	A			
5.011E+05	-4.06E+01	A			
6.309E+05	-3.91E+01	A			
7.943E+05	-3.75E+01	A			
1.000E+06	-3.57E+01	A			
1.258E+06	-3.38E+01	A			
1.584E+06	-3.19E+01	A			
1.995E+06	-3.00E+01	A			
2.511E+06	-2.80E+01	A			
3.162E+06	-2.61E+01	A			
3.981E+06	-2.41E+01	A			
5.011E+06	-2.21E+01	A			
6.309E+06	-2.01E+01	A			
7.943E+06	-1.80E+01	A			
1.000E+07	-1.60E+01	A			
1.258E+07	-1.39E+01	A			
1.584E+07	-1.18E+01	A			
1.995E+07	-9.72E+00	A			
2.511E+07	-7.47E+00	A			

DIFFERENTIAL AMP, DIFFERENTIAL MODE

```

VCC 1 0 5V
VEE 9 0 -5V
IEE 7 9 1MA
REE 7 9 300K
CEE 7 9 2PF
RL1 1 2 3K
RL2 1 8 3K
Q1 2 3 7 NPN
RS1 4 3 5K
Q2 8 6 7 NPN
RS2 5 6 5K
VID 4 0 0V AC
EVID 0 5 4 0 1
.TF V(2) VID
.PLOT AC VDB(2)
.AC DEC 10 10K 20MEG
.MODEL NPN NPN IS=1E-16A BF=200
+ RB=300 CJC=0.3PF CJS=0 TF=302PS
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(2)/VID      = -3.857E+01
INPUT RESISTANCE AT VID      = 1.555E+04
OUTPUT RESISTANCE AT V(2)    = 3.000E+03

```

***** AC ANALYSIS

TNOM= 27.000 TEMP= 27.000

FREQ	VDB(2)	1.000E+01	2.000E+01	4.000E+01	5.000E+01
9.999E+03	3.17E+01	A			
1.258E+04	3.17E+01	A			
1.584E+04	3.17E+01	A			
1.995E+04	3.17E+01	A			
2.511E+04	3.17E+01	A			
3.162E+04	3.17E+01	A			
3.981E+04	3.17E+01	A			
5.011E+04	3.17E+01	A			
6.309E+04	3.17E+01	A			
7.943E+04	3.17E+01	A			
1.000E+05	3.17E+01	A			
1.258E+05	3.17E+01	A			
1.584E+05	3.17E+01	A			
1.995E+05	3.17E+01	A			
2.511E+05	3.16E+01	A			
3.162E+05	3.16E+01	A			
3.981E+05	3.16E+01	A			
5.011E+05	3.15E+01	A			
6.309E+05	3.15E+01	A			
7.943E+05	3.14E+01	A			
1.000E+06	3.12E+01	A			
1.258E+06	3.09E+01	A			
1.584E+06	3.05E+01	A			
1.995E+06	2.99E+01	A			
2.511E+06	2.92E+01	A			
3.162E+06	2.82E+01	A			
3.981E+06	2.70E+01	A			
5.011E+06	2.55E+01	A			
6.309E+06	2.39E+01	A			
7.943E+06	2.22E+01	A			
1.000E+07	2.04E+01	A			
1.258E+07	1.85E+01	A			
1.584E+07	1.66E+01	A			
1.995E+07	1.46E+01	A			
2.511E+07	1.27E+01	A			

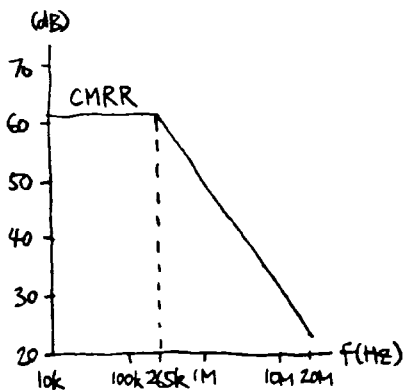
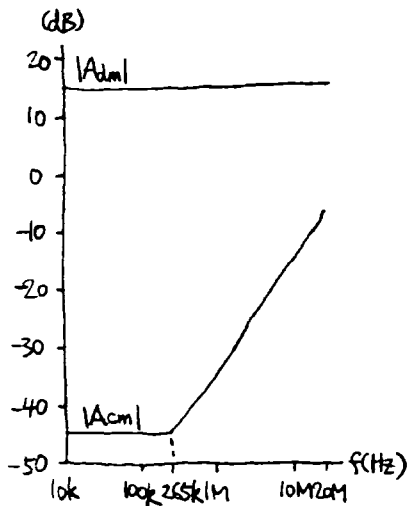
7.7

$$\begin{aligned}
 A_{cm} &\approx -\frac{R_L}{2R_T}(1+SR_TC_T) \\
 &= -\frac{3}{2 \times 300}(1+5 \times 300 \times 10^3 \times 2 \times 10^{-12}) \\
 &= -5 \times 10^{-3}(1+6 \times 10^{-7}s)
 \end{aligned}$$

To calculate A_{dm} , the dominant pole is

$$\begin{aligned}
 |p| &= \frac{1}{R_s[C_{gs}+C_{gd}(1+g_m R_L)]} \\
 &= \frac{1}{5 \times 10^3[98+14(1+1.8 \times 10^{-3} \times 3 \times 10^3)] \times 10^{-15}} \\
 &= 1.1 \times 10^9 \text{ rad/s} \\
 A_{dm} &= \frac{-g_m R_L}{1+s/|p|} = \frac{-1.8 \times 10^{-3} \times 3 \times 10^3}{1+s/(1.1 \times 10^9)} \\
 &= -\frac{5.4}{1+s/(1.1 \times 10^9)}
 \end{aligned}$$

$$CMRR = \frac{|A_{dm}|}{|A_{cm}|} = 1.1 \times 10^3 \frac{1+s/(1.7 \times 10^6)}{1+s/(1.1 \times 10^9)}$$



DIFFERENTIAL AMP, COMMON MODE

```

VDD 1 0 5V
VSS 9 0 -5V
ISS 7 9 1MA
RSS 7 9 300K
CSS 7 9 2PF
RL1 1 2 3K
RL2 1 8 3K
M1 2 3 7 7 CMOSN W=100U L=2U
RS1 4 3 5K
M2 8 6 7 7 CMOSN W=100U L=2U
RS2 5 6 5K
VIC 4 0 -3.514V AC
EVIC 5 0 4 0 1
.TF V(2) VIC
.PLOT AC VDB(2)
.AC DEC 10 10K 20MEG
* COX'=0.7FF/UM**2=BOX/TOX => TOX=500 ANGSTROMS
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0 VTO=0.7 KP=60U LD=0.2U TOX=500E-10
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

```

***** OPERATING POINT INFORMATION          TNOM= 27.000 TEMP= 27.000
+0.1      = 5.000E+00 0:2      = 3.498E+00 0:3      = -3.514E+00
+0.4      = -3.514E+00 0:5      = -3.514E+00 0:6      = -3.514E+00
+0.7      = -4.730E+00 0:8      = 3.498E+00 0:9      = -5.000E+00

```

**** MOSFETS

```

ELEMENT 0:M1      0:M2
MODEL    0:CMOSN  0:CMOSN
ID       5.004E-04 5.004E-04
IBS      0.        0.
IBD      -8.229E-14 -8.229E-14
VGS      1.216E+00 1.216E+00
VDS      8.229E+00 8.229E+00
VBS      0.        0.
VTH      7.000E-01 7.000E-01
VDSAT    5.166E-01 5.166E-01
BETA     3.750E-03 3.750E-03
GAM KFF   0.        0.
GM       1.937E-03 1.937E-03
GDS      0.        0.
GMS      0.        0.
CUTOT    1.503E-14 1.503E-14
CGTOT    1.058E-13 1.058E-13
CBTOT    8.748E-14 8.748E-14
CPTOT    3.344E-15 3.344E-15
CGS      8.748E-14 8.748E-14
CGD      1.503E-14 1.503E-14

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(2)/VIC = -4.996E-03

***** AC ANALYSIS

TNOM= 27.000 TEMP= 27.000

```

FREQ      VDB(2)
A          -6.000E+01 -4.000E+01 -2.000E+01 0. 2.000E+01
+-----+-----+-----+-----+-----+
9.999E+03 -4.60E+01 -A-
1.258E+04 -4.60E+01 + A + + + + + + +
1.584E+04 -4.60E+01 + A + + + + + + +
1.995E+04 -4.60E+01 + A + + + + + + +
2.511E+04 -4.59E+01 + A + + + + + + +
3.162E+04 -4.59E+01 + A + + + + + + +
3.981E+04 -4.59E+01 + A + + + + + + +
5.011E+04 -4.58E+01 + A + + + + + + +
6.309E+04 -4.58E+01 + A + + + + + + +
7.943E+04 -4.56E+01 + A + + + + + + +
1.000E+05 -4.54E+01 -A-
1.258E+05 -4.51E+01 + A + + + + + + +
1.584E+05 -4.47E+01 + A + + + + + + +
1.995E+05 -4.41E+01 + A + + + + + + +
2.511E+05 -4.33E+01 + A + + + + + + +
3.162E+05 -4.22E+01 + A + + + + + + +
3.981E+05 -4.10E+01 + A + + + + + + +
5.011E+05 -3.95E+01 + A + + + + + + +
6.309E+05 -3.79E+01 + A + + + + + + +
7.943E+05 -3.61E+01 + A + + + + + + +
1.000E+06 -3.43E+01 -A-
1.258E+06 -3.24E+01 + + + A + + + + +
1.584E+06 -3.05E+01 + + + A + + + + +
1.995E+06 -2.85E+01 + + + A + + + + +
2.511E+06 -2.65E+01 + + + A + + + + +
3.162E+06 -2.46E+01 + + + A + + + + +
3.981E+06 -2.26E+01 + + + A + + + + +
5.011E+06 -2.06E+01 + + + A + + + + +
6.309E+06 -1.86E+01 + + + A + + + + +
7.943E+06 -1.66E+01 + + + A + + + + +
1.000E+07 -1.46E+01 -A-
1.258E+07 -1.26E+01 + + + + A + + + +
1.584E+07 -1.06E+01 + + + + A + + + +
1.995E+07 -8.59E+00 + + + + A + + + +
2.511E+07 -6.58E+00 + + + + A + + + +
+-----+-----+-----+-----+-----+

```

DIFFERENTIAL AMP, DIFFERENTIAL MODE

```

VDD 1 0 5V
VSS 9 0 -5V
ISS 7 9 1MA
RSS 7 9 300K
CSS 7 9 2PF
RL1 1 2 3K
RL2 1 8 3K
M1 2 3 7 7 CMOSN W=100U L=2U
RS1 4 3 5K
M2 8 6 7 7 CMOSN W=100U L=2U
RS2 5 6 5K
VID 4 10 0 AC
EVID 10 5 4 10 1
VBIAS 10 0 -3.514V
.TF V(2) VID
.PLOT AC VDB(2)
.AC DEC 10 10K 20MEG
* COX'=0.7FF/UM**2=BOX/TOX => TOX=500 ANGSTROMS
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0 VTO=0.7 KP=60U LD=0.2U TOX=500E-10
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(2)/VID = -5.812E+00

***** AC ANALYSIS

TNOM= 27.000 TEMP= 27.000

```

FREQ      VDB(2)
A          1.515E+01 1.520E+01 1.525E+01 1.530E+01 1.535E+01
+-----+-----+-----+-----+-----+
9.999E+03 1.52E+01 -A-
1.258E+04 1.52E+01 + + + + A + + + +
1.584E+04 1.52E+01 + + + + A + + + +
1.995E+04 1.52E+01 + + + + A + + + +
2.511E+04 1.52E+01 + + + + A + + + +
3.162E+04 1.52E+01 + + + + A + + + +
3.981E+04 1.52E+01 + + + + A + + + +
5.011E+04 1.52E+01 + + + + A + + + +
6.309E+04 1.52E+01 + + + + A + + + +
7.943E+04 1.52E+01 + + + + A + + + +
1.000E+05 1.52E+01 -A-
1.258E+05 1.52E+01 + + + + A + + + +
1.584E+05 1.52E+01 + + + + A + + + +
1.995E+05 1.52E+01 + + + + A + + + +
2.511E+05 1.52E+01 + + + + A + + + +
3.162E+05 1.52E+01 + + + + A + + + +
3.981E+05 1.52E+01 + + + + A + + + +
5.011E+05 1.52E+01 + + + + A + + + +
6.309E+05 1.52E+01 + + + + A + + + +
7.943E+05 1.52E+01 + + + + A + + + +
1.000E+06 1.52E+01 -A-
1.258E+06 1.52E+01 + + + + A + + + +
1.584E+06 1.52E+01 + + + + A + + + +
1.995E+06 1.52E+01 + + + + A + + + +
2.511E+06 1.52E+01 + + + + A + + + +
3.162E+06 1.52E+01 + + + + A + + + +
3.981E+06 1.52E+01 + + + + A + + + +
5.011E+06 1.52E+01 + + + + A + + + +
6.309E+06 1.52E+01 + + + + A + + + +
7.943E+06 1.52E+01 + + + + A + + + +
1.000E+07 1.52E+01 -A-
1.258E+07 1.52E+01 + + + + A + + + +
1.584E+07 1.52E+01 + + + + A + + + +
1.995E+07 1.52E+01 + + + + A + + + +
2.511E+07 1.51E+01 + A + + + + + + + + +
+-----+-----+-----+-----+-----+

```

1.8

$$\frac{v_o}{v_i} = \frac{g_m R_E + \frac{R_E}{r_\pi}}{1 + g_m R_E + \frac{R_b + R_E}{r_\pi}} \frac{1 - \frac{s}{z_1}}{1 - \frac{s}{p_1}}$$

$$= \frac{\frac{0.3 \times 4000}{26} + \frac{4000}{50}}{1 + \frac{0.3 \times 4000}{26} + \frac{4450}{50}} \frac{0.3}{26} \frac{1 - \frac{j\omega}{z_1}}{1 - \frac{j\omega}{p_1}}$$

$$= 0.977 \frac{1 - j\frac{\omega}{z_1}}{1 - j\frac{\omega}{p_1}}$$

$$z_1 = -\frac{g_m}{C_\pi} = -\omega_T = -2\pi \times 4 \times 10^6$$

$$= -25.1 \times 10^6 \text{ rad/sec}$$

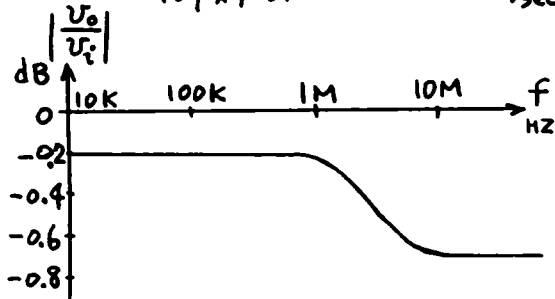
$$p_1 = -\frac{1}{C_\pi R_1}$$

$$R_1 = r_\pi \parallel \frac{R_b + R_E}{1 + g_m R_E} = \frac{50 \times 26}{0.3} \parallel \frac{450 + 4000}{1 + \frac{0.3 \times 4000}{26}}$$

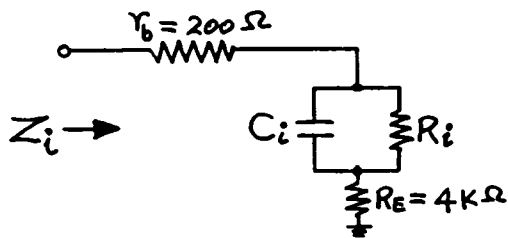
$$= 4333 \parallel 94.4 = 92.4 \Omega$$

$$C_\pi = \frac{g_m}{\omega_T} = \frac{0.3}{26} \frac{1}{2\pi \times 4 \times 10^6} = 459 \text{ pF}$$

$$\therefore p_1 = -\frac{10^{12}}{459 \times 92.4} = -23.6 \times 10^6 \text{ rad/sec}$$



1.9

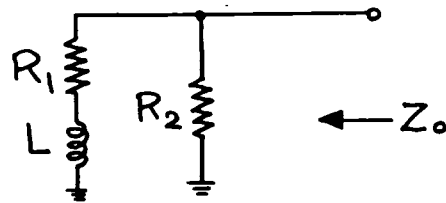


$$C_i = \frac{C_\pi}{1 + g_m R_E} = \frac{459}{1 + \frac{0.3 \times 4000}{26}} = 9.73 \text{ pF}$$

$$R_i = (1 + g_m R_E) r_\pi = \left(1 + \frac{0.3 \times 4000}{26}\right) \times \frac{50 \times 26}{0.3}$$

$$= 204 \text{ K}\Omega$$

$$Z_i = 4.2 \text{ K}\Omega + 204 \text{ K}\Omega \parallel \frac{1}{j\omega C_i}$$

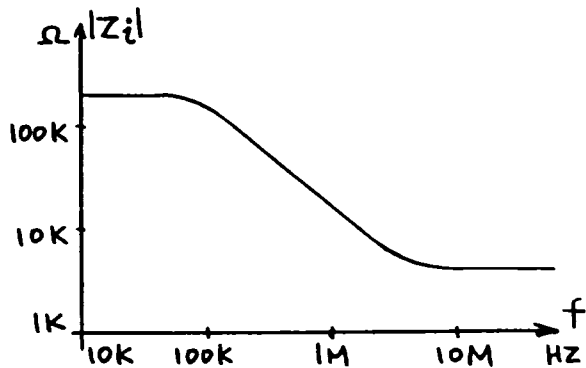
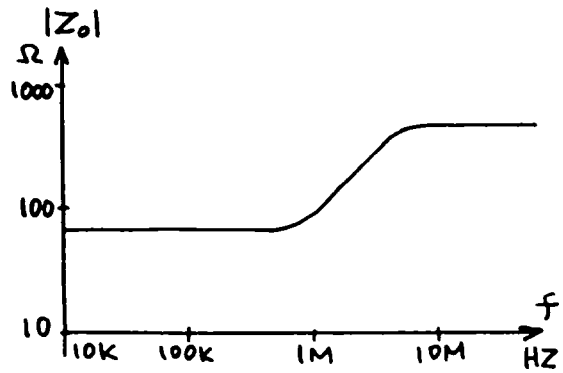


$$R_1 = \frac{1}{g_m} + \frac{R_b}{\beta_o} = \frac{26}{0.3} + \frac{450}{50} = 95.7 \Omega$$

$$R_2 = R_b = 450 \Omega$$

$$L = C_\pi r_\pi \frac{R_b}{\beta_o} = 459 \times \frac{50 \times 26}{0.3} \times \frac{450}{50} \times 10^{-12}$$

$$= 17.9 \mu\text{H}$$



7-11

```

PNP EMITTER FOLLOWER, RESISTIVE LOAD
* DC VO=0V, 300UA*4K=1.2V=VCC
VCC 1 0 1.2V
VEE 2 0 -1.2V
RE 1 5 4K
Q1 2 4 5 PNP
RS 3 4 250
RLOAD 5 0 1K
VBIAS 3 6 -0.745V AC
VPULSE 6 0 PULSE 0V 1MV 1NS 0NS 0NS 100NS
.TRAN 0.25MS 10MS
.PLOT TRAN V(5)
.MODEL PNP PNP IS=1E-16A BF=50
+ RB=200 CJE=0 CJC=0 CJS=0 TF=39.8NS
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

```

+0:1      = 1.200E+00 0:2      =-1.200E+00 0:3      =-7.450E-01
+0:4      =-7.435E-01 0:5      = 1.819E-04 0:6      = 0.

```

**** BIPOLAR JUNCTION TRANSISTORS

```

ELEMENT 0:Q1
MODEL 0:PNP
IB -5.878E-06
IC -2.939E-04
VBE -7.437E-01
VCE -1.200E+00
VBC 4.565E-01
VS 7.424E-01
POWER 3.571E-04
BETAD 5.000E+01
GM 1.137E-02
RPI 4.400E+03
RX 2.000E+02
RO 4.576E+15
CPI 4.522E-10
CMU 0.
CBX 0.
CCS 0.
BETAAC 5.000E+01
FT 3.998E+06

```

***** TRANSIENT ANALYSIS TNOM= 27.000 TEMP= 27.000

```

TIME V(5)
(A ) 0. -5.000E-04 0. 5.000E-04 1.000E-03 1.500E-03
0. 1.82E-04 +-----A-----+
2.500E-10 1.82E-04 + + A + + + + +
5.000E-10 1.82E-04 + + A + + + + +
7.500E-10 1.82E-04 + + A + + + + +
1.000E-09 1.82E-04 + + A + + + + +
1.250E-09 8.23E-04 + + + + A + + +
1.500E-09 8.24E-04 + + + + A + + +
1.750E-09 8.25E-04 + + + + A + + +
2.000E-09 8.26E-04 + + + + A + + +
2.250E-09 8.27E-04 + + + + A + + +
2.500E-09 8.28E-04 +-----A-----+
2.750E-09 8.29E-04 + + + + A + + +
3.000E-09 8.31E-04 + + + + A + + +
3.250E-09 8.32E-04 + + + + A + + +
3.500E-09 8.33E-04 + + + + A + + +
3.750E-09 8.34E-04 + + + + A + + +
4.000E-09 8.35E-04 + + + + A + + +
4.250E-09 8.36E-04 + + + + A + + +
4.500E-09 8.37E-04 + + + + A + + +
4.750E-09 8.38E-04 +-----A-----+
5.000E-09 8.39E-04 + + + + A + + +
5.250E-09 8.40E-04 + + + + A + + +
5.500E-09 8.42E-04 + + + + A + + +
5.750E-09 8.43E-04 + + + + A + + +
6.000E-09 8.44E-04 + + + + A + + +
6.250E-09 8.45E-04 + + + + A + + +
6.500E-09 8.46E-04 + + + + A + + +
6.750E-09 8.47E-04 + + + + A + + +
7.000E-09 8.48E-04 + + + + A + + +
7.250E-09 8.49E-04 + + + + A + + +
7.500E-09 8.50E-04 +-----A-----+
7.750E-09 8.51E-04 + + + + A + + +

```

```

PNP EMITTER FOLLOWER, CAPACITIVE LOAD
VCC 1 0 1.2V
VEE 2 0 -1.2V
IER 1 5 300UA
Q1 2 4 5 PNP
RS 3 4 250
CLOAD 5 0 400PF
VBIAS 3 6 -0.745V AC
VPULSE 6 0 PULSE 0V 1MV 1NS 0NS 0NS 1300NS
.TRAN 20NS 800NS

```

```

.PLOT TRAN V(5)
.MODEL PNP PNP IS=1E-16A BF=50
+ RB=200 CJE=0 CJC=0 CJS=0 TF=39.8NS
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

**** BIPOLAR JUNCTION TRANSISTORS

```

ELEMENT 0:Q1
MODEL 0:PNP
IB -5.882E-06
IC -2.941E-04
VBE -7.437E-01
VCE -1.200E+00
VBC 4.565E-01
VS 7.424E-01
POWER 3.574E-04
BETAD 5.000E+01
GM 1.137E-02
RPI 4.396E+03
RX 2.000E+02
RO 4.576E+15
CPI 4.526E-10
CMU 0.
CBX 0.
CCS 0.
BETAAC 5.000E+01
FT 3.998E+06

```

***** TRANSIENT ANALYSIS TNOM= 27.000 TEMP= 27.000

```

TIME V(5)
(A ) 0. 5.000E-04 1.000E-03 1.500E-03 2.000E-03
0. 2.03E-04 +-----A-----+
2.000E-08 2.59E-04 + A + + + + +
4.000E-08 3.94E-04 + + A + + + + +
6.000E-08 5.42E-04 + + A + + + + +
8.000E-08 6.95E-04 + + A + + + + +
1.000E-07 8.44E-04 + + A + + + + +
1.200E-07 9.81E-04 + + A + + + + +
1.400E-07 1.10E-03 + + A + + + + +
1.600E-07 1.21E-03 + + A + + + + +
1.800E-07 1.29E-03 + + A + + + + +
2.000E-07 1.35E-03 +-----A-----+
2.200E-07 1.39E-03 + + A + + + + +
2.400E-07 1.42E-03 + + A + + + + +
2.600E-07 1.43E-03 + + A + + + + +
2.800E-07 1.42E-03 + + A + + + + +
3.000E-07 1.41E-03 + + A + + + + +
3.200E-07 1.39E-03 + + A + + + + +
3.400E-07 1.36E-03 + + A + + + + +
3.600E-07 1.33E-03 + + A + + + + +
3.800E-07 1.30E-03 + + A + + + + +
4.000E-07 1.27E-03 +-----A-----+
4.200E-07 1.24E-03 + + A + + + + +
4.400E-07 1.22E-03 + + A + + + + +
4.600E-07 1.20E-03 + + A + + + + +
4.800E-07 1.18E-03 + + A + + + + +
5.000E-07 1.17E-03 + + A + + + + +
5.200E-07 1.16E-03 + + A + + + + +
5.400E-07 1.16E-03 + + A + + + + +
5.600E-07 1.16E-03 + + A + + + + +
5.800E-07 1.16E-03 + + A + + + + +
6.000E-07 1.16E-03 +-----A-----+
6.200E-07 1.17E-03 + + A + + + + +
6.400E-07 1.17E-03 + + A + + + + +
6.600E-07 1.19E-03 + + A + + + + +
6.800E-07 1.19E-03 + + A + + + + +
7.000E-07 1.19E-03 + + A + + + + +
7.200E-07 1.20E-03 + + A + + + + +
7.400E-07 1.20E-03 + + A + + + + +
7.600E-07 1.20E-03 + + A + + + + +
7.800E-07 1.21E-03 + + A + + + + +
8.000E-07 1.21E-03 +-----A-----+

```

CAPACITIVE LOAD RESULTS IN SOME PEAKING [V(5) JUMPS BY > 1MV]

7-12

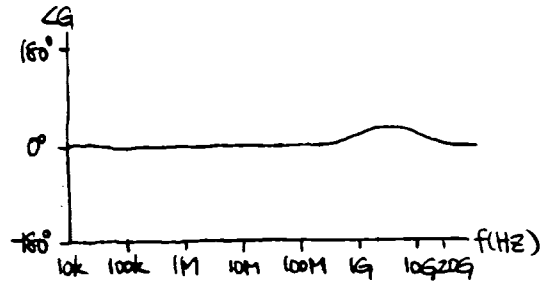
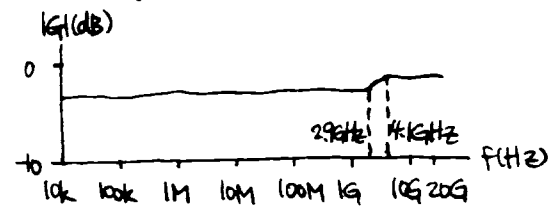
$$\frac{7.10}{\frac{V_o}{V_i} = \frac{g_m R_L}{1 + g_m R_L} \frac{1 + s/|Z|}{1 + s/|P|} = G(s)}$$

$$\frac{g_m R_L}{1 + g_m R_L} = \frac{1.8 \times 10^{-3} \times 10^3}{1 + 1.8 \times 10^{-3} \times 10^3} = 0.64$$

$$|Z| = \frac{g_m}{C_s} = \frac{1.8 \times 10^{-3}}{98 \times 10^{-15}} = 1.8 \times 10^{10} \text{ rad/s}$$

$$|P| = \frac{1}{\frac{C_{gs} R_s + R_L}{1 + g_m R_L}} = \frac{1}{98 \times 10^{-15} \frac{100 + 10^3}{1 + 1.8 \times 10^{-3} \times 10^3}}$$

$$= 2.6 \times 10^{10} \text{ rad/s}$$



7-13

SOURCE FOLLOWER, RESISTIVE LOAD

```

VDD 1 0 5V
RL 4 0 1K
M1 1 2 4 4 CMOSN W=100U L=2U
RS 3 2 250
VBIAS 3 6 1.716V AC
VPULSE 6 0 PULSE 0V 1MV 1NS 0NS 0NS 100NS
.AC DEC 10 10K 20GIG
.PLOT AC VDB(4)
.PLOT AC VP(4)
.TRAN 0.25NS 10NS
.PLOT TRAN V(4)
* COX'=0.7FF/UM**2=EOX/TOX => TOX=500 ANGSTROMS
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0 VTO=0.7 KP=60U LD=0.2U TOX=500E-10
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

```

+0:1      = 5.000E+00 0:2      = 1.716E+00 0:3      = 1.716E+00
+0:4      = 4.997E-01 0:6      = 0.

```

**** MOSFETS

```

ELEMENT 0:M1
MODEL 0:CMOSN
ID 4.997E-04
IBS 0.
IBD -4.500E-14
VGS 1.216E+00
VDS 4.500E+00
VBS 0.
VTH 7.000E-01
VDSAT 5.163E-01
BETA 3.750E-03
GAM EFF 0.
GM 1.936E-03
GDS 0.
GMB 0.
CITOT 1.448E-14
CGTOT 1.053E-13
CSTOT 8.748E-14
CBTOT 3.347E-15
CGS 8.748E-14
CGD 1.448E-14

```

***** AC ANALYSIS

TNOM= 27.000 TEMP= 27.000

FREQ	VDB(4)					
9.999E+03	-3.61E+00	-A				
1.258E+04	-3.61E+00	A				
1.584E+04	-3.61E+00	A				
1.995E+04	-3.61E+00	A				
2.511E+04	-3.61E+00	A				
3.162E+04	-3.61E+00	A				
3.981E+04	-3.61E+00	A				
5.011E+04	-3.61E+00	A				
6.309E+04	-3.61E+00	A				
7.943E+04	-3.61E+00	A				
1.000E+05	-3.61E+00	A				
1.258E+05	-3.61E+00	A				
1.584E+05	-3.61E+00	A				
1.995E+05	-3.61E+00	A				
2.511E+05	-3.61E+00	A				
3.162E+05	-3.61E+00	A				
3.981E+05	-3.61E+00	A				
5.011E+05	-3.61E+00	A				
6.309E+05	-3.61E+00	A				
7.943E+05	-3.61E+00	A				
1.000E+06	-3.61E+00	A				
1.258E+06	-3.61E+00	A				
1.584E+06	-3.61E+00	A				
1.995E+06	-3.61E+00	A				
2.511E+06	-3.61E+00	A				
3.162E+06	-3.61E+00	A				
3.981E+06	-3.61E+00	A				
5.011E+06	-3.61E+00	A				
6.309E+06	-3.61E+00	A				
7.943E+06	-3.61E+00	A				
1.000E+07	-3.61E+00	A				
1.258E+07	-3.61E+00	A				
1.584E+07	-3.61E+00	A				
1.995E+07	-3.61E+00	A				
2.511E+07	-3.61E+00	A				
3.162E+07	-3.61E+00	A				
3.981E+07	-3.61E+00	A				
5.011E+07	-3.61E+00	A				
6.309E+07	-3.61E+00	A				
7.943E+07	-3.61E+00	A				
1.000E+08	-3.61E+00	A				
1.258E+08	-3.61E+00	A				
1.584E+08	-3.61E+00	A				
1.995E+08	-3.61E+00	A				
2.511E+08	-3.61E+00	A				
3.162E+08	-3.60E+00	A				
3.981E+08	-3.60E+00	A				
5.011E+08	-3.59E+00	A				
6.309E+08	-3.57E+00	A				
7.943E+08	-3.55E+00	A				
1.000E+09	-3.51E+00	A				
1.258E+09	-3.46E+00	A				
1.584E+09	-3.38E+00	A				
1.995E+09	-3.28E+00	A				
2.511E+09	-3.15E+00	A				
3.162E+09	-2.99E+00	A				
3.981E+09	-2.83E+00	A				
5.011E+09	-2.67E+00	A				
6.309E+09	-2.55E+00	A				
7.943E+09	-2.46E+00	A				
1.000E+10	-2.43E+00	A				
1.258E+10	-2.44E+00	A				
1.584E+10	-2.52E+00	A				
1.995E+10	-2.68E+00	A				
2.511E+10	-2.93E+00	A				

7-14

FREQ	VP(4)					
(A)		-3.000E+01	-2.000E+01	-1.000E+01	0.	1.000E+01
9.999E+03	1.67E-05				A	
1.258E+04	2.10E-05				A	
1.584E+04	2.64E-05				A	
1.995E+04	3.32E-05				A	
2.511E+04	4.18E-05				A	
3.162E+04	5.27E-05				A	
3.981E+04	6.63E-05				A	
5.011E+04	8.35E-05				A	
6.309E+04	1.05E-04				A	
7.943E+04	1.32E-04				A	
1.000E+05	1.67E-04				A	
1.258E+05	2.10E-04				A	
1.584E+05	2.64E-04				A	
1.995E+05	3.32E-04				A	
2.511E+05	4.18E-04				A	
3.162E+05	5.27E-04				A	
3.981E+05	6.63E-04				A	
5.011E+05	8.35E-04				A	
6.309E+05	1.05E-03				A	
7.943E+05	1.32E-03				A	
1.000E+06	1.67E-03				A	
1.258E+06	2.10E-03				A	
1.584E+06	2.64E-03				A	
1.995E+06	3.32E-03				A	
2.511E+06	4.18E-03				A	
3.162E+06	5.27E-03				A	
3.981E+06	6.63E-03				A	
5.011E+06	8.35E-03				A	
6.309E+06	1.05E-02				A	
7.943E+06	1.32E-02				A	
1.000E+07	1.67E-02				A	
1.258E+07	2.10E-02				A	
1.584E+07	2.64E-02				A	
1.995E+07	3.32E-02				A	
2.511E+07	4.18E-02				A	
3.162E+07	5.27E-02				A	
3.981E+07	6.63E-02				A	
5.011E+07	8.34E-02				A	
6.309E+07	1.05E-01				A	
7.943E+07	1.32E-01				A	
1.000E+08	1.66E-01				A	
1.258E+08	2.09E-01				A	
1.584E+08	2.63E-01				A	
1.995E+08	3.31E-01				A	
2.511E+08	4.15E-01				A	
3.162E+08	5.20E-01				A	
3.981E+08	6.51E-01				A	
5.011E+08	8.10E-01				A	
6.309E+08	1.00E+00				A	
7.943E+08	1.22E+00				A	
1.000E+09	1.48E+00				A	
1.258E+09	1.74E+00				A	
1.584E+09	1.97E+00				A	
1.995E+09	2.10E+00				A	
2.511E+09	2.04E+00				A	
3.162E+09	1.67E+00				A	
3.981E+09	8.85E-01				A	
5.011E+09	-3.68E-01				A	
6.309E+09	-2.09E+00				A	
7.943E+09	-4.26E+00				A	
1.000E+10	-6.87E+00				A	
1.258E+10	-9.96E+00			A		
1.584E+10	-1.35E+01			A		
1.995E+10	-1.78E+01		A			
2.511E+10	-2.28E+01	A				

***** TRANSIENT ANALYSIS TNUM= 27.000 TEMP= 27.000

TIME	V(4)				
(A)		4.995E-01	5.000E-01	5.005E-01	5.010E-01
0.	5.00E-01		A		
2.500E-10	5.00E-01		A		
5.000E-10	5.00E-01		A		
7.500E-10	5.00E-01		A		
1.000E-09	5.00E-01		A		
1.250E-09	5.00E-01			A	
1.500E-09	5.00E-01			A	
1.750E-09	5.00E-01			A	
2.000E-09	5.00E-01			A	
2.250E-09	5.00E-01			A	
2.500E-09	5.00E-01			A	
2.750E-09	5.00E-01			A	
3.000E-09	5.00E-01			A	
3.250E-09	5.00E-01			A	
3.500E-09	5.00E-01			A	
3.750E-09	5.00E-01			A	
4.000E-09	5.00E-01			A	
4.250E-09	5.00E-01			A	
4.500E-09	5.00E-01			A	
4.750E-09	5.00E-01			A	
5.000E-09	5.00E-01			A	
5.250E-09	5.00E-01			A	
5.500E-09	5.00E-01			A	
5.750E-09	5.00E-01			A	
6.000E-09	5.00E-01			A	
6.250E-09	5.00E-01			A	
6.500E-09	5.00E-01			A	
6.750E-09	5.00E-01			A	
7.000E-09	5.00E-01			A	
7.250E-09	5.00E-01			A	
7.500E-09	5.00E-01			A	
7.750E-09	5.00E-01			A	
8.000E-09	5.00E-01			A	
8.250E-09	5.00E-01			A	
8.500E-09	5.00E-01			A	
8.750E-09	5.00E-01			A	
9.000E-09	5.00E-01			A	
9.250E-09	5.00E-01			A	
9.500E-09	5.00E-01			A	
9.750E-09	5.00E-01			A	
1.000E-08	5.00E-01			A	

SOURCE FOLLOWER, CAPACITIVE LOAD
VDD 1 0 5V
IL 4 0 0.5MA
CL 4 0 400PF
M1 1 2 4 4 CMOSN W=100U L=2U
RS 3 2 250
VBIAS 3 6 1.716V AC
VPULSE 6 0 PULSE 0V 1MV 1NS 0NS 0NS 100NS
.AC DEC 10 10K 20GIG
.PLOT AC VDB(4)
.PLOT AC VP(4)
.TRAN 20NS 800NS
.PLOT TRAN V(4)
* COX'=0.7FF/UM**2=EOX/TOX => TOX=500 ANGSTROMS
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0 VTO=0.7 KP=60U LD=0.2U TOX=500E-10
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

***** OPERATING POINT INFORMATION TNUM= 27.000 TEMP= 27.000

+0:1 = 5.000E+00 0:2 = 1.716E+00 0:3 = 1.716E+00
+0:4 = 4.996E-01 0:6 = 0.

7-15

***** AC ANALYSIS

TNCN= 27.000 TEMP= 27.000

FREQ (A)	VDB(4) -1.500E+02	-1.000E+02	-5.000E+01	0.	5.000E+01	FREQ (A)	VP(4) -1.500E+02	-1.000E+01	-5.000E+01	0.	5.000E+01
9.999E+03	-7.32E-04					9.999E+03	-7.44E-01				A
1.258E+04	-1.16E-03				A	1.258E+04	-9.36E-01				A
1.584E+04	-1.84E-03				A	1.584E+04	-1.17E+00				A
1.995E+04	-2.91E-03				A	1.995E+04	-1.48E+00				A
2.511E+04	-4.61E-03				A	2.511E+04	-1.86E+00				A
3.162E+04	-7.31E-03				A	3.162E+04	-2.35E+00				A
3.981E+04	-1.16E-02				A	3.981E+04	-2.95E+00				A
5.011E+04	-1.83E-02				A	5.011E+04	-3.72E+00				A
6.309E+04	-2.90E-02				A	6.309E+04	-4.68E+00				A
7.943E+04	-4.59E-02				A	7.943E+04	-5.88E+00				A
1.000E+05	-7.26E-02				A	1.000E+05	-7.39E+00				A
1.258E+05	-1.14E-01				A	1.258E+05	-9.28E+00				A
1.584E+05	-1.80E-01				A	1.584E+05	-1.18E+01				A
1.995E+05	-2.82E-01				A	1.995E+05	-1.45E+01				A
2.511E+05	-4.39E-01				A	2.511E+05	-1.80E+01				A
3.162E+05	-6.76E-01				A	3.162E+05	-2.23E+01				A
3.981E+05	-1.02E+00				A	3.981E+05	-2.73E+01				A
5.011E+05	-1.53E+00				A	5.011E+05	-3.30E+01				A
6.309E+05	-2.22E+00				A	6.309E+05	-3.93E+01				A
7.943E+05	-3.14E+00				A	7.943E+05	-4.58E+01				A
1.000E+06	-4.28E+00				A	1.000E+06	-5.23E+01				A
1.258E+06	-5.64E+00				A	1.258E+06	-5.85E+01				A
1.584E+06	-7.18E+00				A	1.584E+06	-6.40E+01				A
1.995E+06	-8.86E+00				A	1.995E+06	-6.88E+01				A
2.511E+06	-1.06E+01				A	2.511E+06	-7.29E+01				A
3.162E+06	-1.25E+01				A	3.162E+06	-7.62E+01				A
3.981E+06	-1.44E+01				A	3.981E+06	-7.90E+01				A
5.011E+06	-1.63E+01				A	5.011E+06	-8.12E+01				A
6.309E+06	-1.83E+01				A	6.309E+06	-8.29E+01				A
7.943E+06	-2.03E+01				A	7.943E+06	-8.44E+01				A
1.000E+07	-2.22E+01				A	1.000E+07	-8.55E+01				A
1.258E+07	-2.42E+01				A	1.258E+07	-8.64E+01				A
1.584E+07	-2.62E+01				A	1.584E+07	-8.71E+01				A
1.995E+07	-2.82E+01				A	1.995E+07	-8.76E+01				A
2.511E+07	-3.02E+01				A	2.511E+07	-8.80E+01				A
3.162E+07	-3.22E+01				A	3.162E+07	-8.83E+01				A
3.981E+07	-3.42E+01				A	3.981E+07	-8.86E+01				A
5.011E+07	-3.62E+01				A	5.011E+07	-8.87E+01				A
6.309E+07	-3.82E+01				A	6.309E+07	-8.88E+01				A
7.943E+07	-4.02E+01				A	7.943E+07	-8.88E+01				A
1.000E+08	-4.22E+01				A	1.000E+08	-8.88E+01				A
1.258E+08	-4.42E+01				A	1.258E+08	-8.87E+01				A
1.584E+08	-4.62E+01				A	1.584E+08	-8.85E+01				A
1.995E+08	-4.82E+01				A	1.995E+08	-8.83E+01				A
2.511E+08	-5.02E+01				A	2.511E+08	-8.79E+01				A
3.162E+08	-5.22E+01				A	3.162E+08	-8.75E+01				A
3.981E+08	-5.42E+01				A	3.981E+08	-8.69E+01				A
5.011E+08	-5.62E+01				A	5.011E+08	-8.62E+01				A
6.309E+08	-5.81E+01				A	6.309E+08	-8.53E+01				A
7.943E+08	-6.01E+01				A	7.943E+08	-8.42E+01				A
1.000E+09	-6.20E+01				A	1.000E+09	-8.29E+01				A
1.258E+09	-6.38E+01				A	1.258E+09	-8.13E+01				A
1.584E+09	-6.57E+01				A	1.584E+09	-7.96E+01				A
1.995E+09	-6.74E+01				A	1.995E+09	-7.77E+01				A
2.511E+09	-6.90E+01				A	2.511E+09	-7.60E+01				A
3.162E+09	-7.06E+01				A	3.162E+09	-7.46E+01				A
3.981E+09	-7.20E+01				A	3.981E+09	-7.37E+01				A
5.011E+09	-7.35E+01				A	5.011E+09	-7.37E+01				A
6.309E+09	-7.49E+01				A	6.309E+09	-7.44E+01				A
7.943E+09	-7.65E+01				A	7.943E+09	-7.58E+01				A
1.000E+10	-7.81E+01				A	1.000E+10	-7.75E+01				A
1.258E+10	-7.98E+01				A	1.258E+10	-7.94E+01				A
1.584E+10	-8.16E+01				A	1.584E+10	-8.12E+01				A
1.995E+10	-8.35E+01				A	1.995E+10	-8.27E+01				A
2.511E+10	-8.54E+01				A	2.511E+10	-8.41E+01				A

***** TRANSIENT ANALYSIS

THOM= 27.000 TEMP= 27.000

TIME	V(4)					
(A)	4.996E-01	4.998E-01	5.000E-01	5.002E-01	5.004E-01	
0.	5.000E-01	A	+	+	+	+
2.000E-08	5.000E-01	+	+	+	+	+
4.000E-08	5.000E-01	+	+	+	+	+
6.000E-08	5.000E-01	+	+	+	+	+
8.000E-08	5.000E-01	+	+	+	+	+
1.000E-07	5.000E-01	+	+	+	+	+
1.200E-07	5.000E-01	+	+	+	+	+
1.400E-07	5.000E-01	+	+	+	+	+
1.600E-07	5.000E-01	+	+	+	+	+
1.800E-07	5.000E-01	+	+	+	+	+
2.000E-07	5.000E-01	+	+	+	+	+
2.200E-07	5.000E-01	+	+	+	+	+
2.400E-07	5.000E-01	+	+	+	+	+
2.600E-07	5.000E-01	+	+	+	+	+
2.800E-07	5.000E-01	+	+	+	+	+
3.000E-07	5.000E-01	+	+	+	+	+
3.200E-07	5.000E-01	+	+	+	+	+
3.400E-07	5.000E-01	+	+	+	+	+
3.600E-07	5.000E-01	+	+	+	+	+
3.800E-07	5.000E-01	+	+	+	+	+
4.000E-07	5.000E-01	+	+	+	+	+
4.200E-07	5.000E-01	+	+	+	+	+
4.400E-07	5.000E-01	+	+	+	+	+
4.600E-07	5.000E-01	+	+	+	+	+
4.800E-07	5.000E-01	+	+	+	+	+
5.000E-07	5.000E-01	+	+	+	+	+
5.200E-07	5.000E-01	+	+	+	+	+
5.400E-07	5.000E-01	+	+	+	+	+
5.600E-07	5.000E-01	+	+	+	+	+
5.800E-07	5.000E-01	+	+	+	+	+
6.000E-07	5.000E-01	+	+	+	+	+
6.200E-07	5.000E-01	+	+	+	+	+
6.400E-07	5.000E-01	+	+	+	+	+
6.600E-07	5.000E-01	+	+	+	+	+
6.800E-07	5.000E-01	+	+	+	+	+
7.000E-07	5.000E-01	+	+	+	+	+
7.200E-07	5.000E-01	+	+	+	+	+
7.400E-07	5.000E-01	+	+	+	+	+
7.600E-07	5.000E-01	+	+	+	+	+
7.800E-07	5.000E-01	+	+	+	+	+
8.000E-07	5.000E-01	+	+	+	+	+

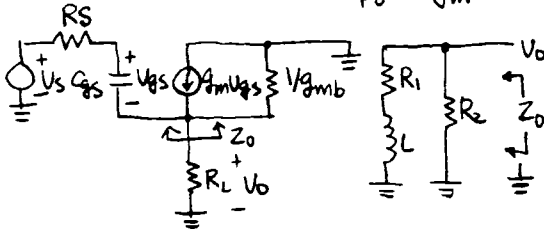
CAPACITIVE LOAD INTRODUCES PEAKING.

7-17

7.11

(a) Use (7.67)–(7.69), and make the replacements:

$$R'_S \rightarrow R_S, \beta_o \rightarrow \infty, G_T \rightarrow C_{gs}, \frac{T_{\pi}}{\beta_o} \rightarrow \frac{1}{g_m}$$



$$R_1 = \frac{1}{g_m}$$

$$R_2 = R_S \parallel \frac{1}{g_{mb}}$$

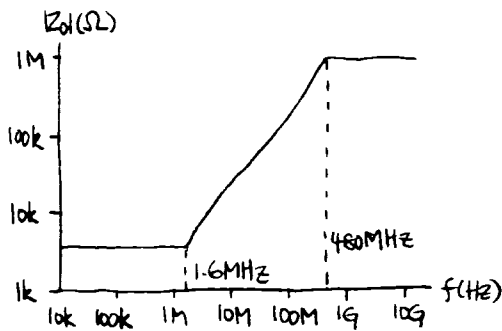
$1/g_{mb}$ can be added in parallel to the R_2 for the bipolar case. Or it can be shown that $R_2 = Z_o(\omega \rightarrow \infty)$ and equals $R_S \parallel \frac{1}{g_{mb}}$ here.

$$L = \frac{R_S C_{gs}}{g_m}$$

$$(b) R_1 = \frac{1}{g_m} = \frac{1}{0.3 \times 10^{-3}} = 3.3 \times 10^3 \Omega = 3.3 \text{ k}\Omega$$

$$R_2 = R_S = 1 \text{ M}\Omega \quad (\gamma = 0 \text{ and no } g_{mb})$$

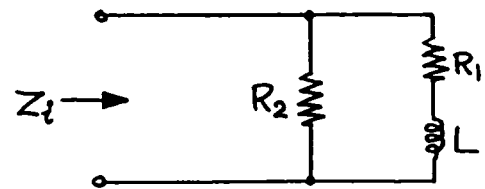
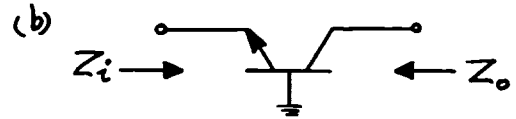
$$L = \frac{R_S C_{gs}}{g_m} = \frac{10^6 \times 100 \times 10^{-15}}{0.3 \times 10^{-3}} = 3.3 \times 10^{-4} \text{ H} = 0.33 \text{ mH}$$

7.12

$$(a) \frac{i_o}{i_i} = \frac{\alpha_o}{1 + j\omega \frac{C_{\pi}}{g_m}} \quad \alpha_o = \frac{\beta_o}{1 + \beta_o} = 0.99$$

$$= \frac{0.99}{1 + j\omega \times 10^{-11} \times 52} = \frac{0.99}{1 + j \frac{\omega}{1.92 \times 10^9}}$$

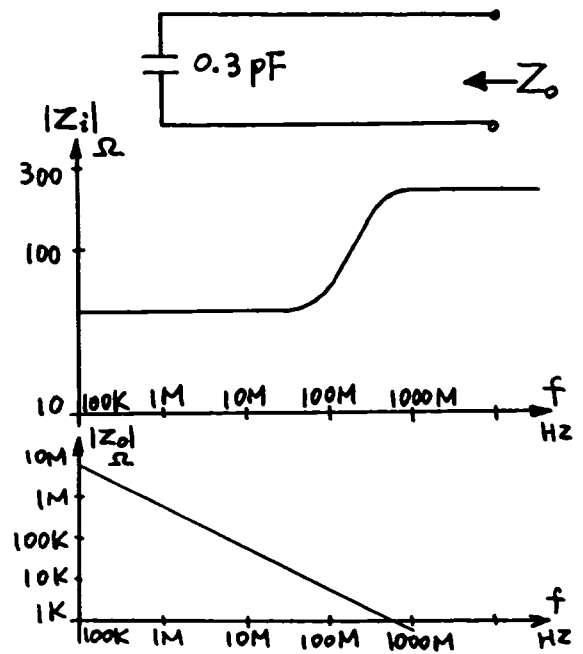
$$\left| \frac{i_o}{i_i} \right| = 0.7 \text{ at } \frac{1}{2\pi} \times 1.92 \times 10^9 = 306 \text{ MHz}$$



$$R_2 = R_b = r_b = 200 \Omega$$

$$R_1 = \frac{1}{g_m} + \frac{R_b}{\beta_o} = 52 + \frac{200}{100} = 54 \Omega$$

$$L = C_{\pi} r_{\pi} \frac{R_b}{\beta_o} = 10^{-11} \times 5200 \times \frac{200}{100} = 0.104 \mu\text{H}$$



7-18

7.14

At low freq.

$$\frac{V_o}{V_i} = - \frac{r_\pi}{r_\pi + R_s} g_m R_L$$

$$= - \frac{5.2K}{5.2K + 10K} \frac{5000}{26} = -65.8$$

Zero value time constant

$$R_{\pi o} = r_\pi \parallel (R_s + r_b)$$

$$= 5.2K \parallel 10K = 3.42K \Omega$$

$$R_{\mu o} = R_{\pi o} + R_L + g_m R_L R_{\pi o}$$

$$= 3.42 + 5 + \frac{5000}{26} \times 3.42$$

$$= 666K \Omega$$

$$R_{Cso} = R_L = 5K \Omega$$

$$C_\pi + C_\mu = \frac{g_m}{2\pi f_T}$$

$$= \frac{1}{2\pi \times 26 \times 600 \times 10^6} = 10.2 pF$$

$$\therefore C_\pi = 10 pF$$

$$\therefore C_\pi R_{\pi o} = 10 \times 3.42 = 34.2 ns$$

$$C_\mu R_{\mu o} = 0.2 \times 666 = 133.2 ns$$

$$C_{Cso} R_{Cso} = 1 \times 5 = 5 ns$$

$$\therefore \Sigma T_o = 34.2 + 133.2 + 5 = 172.4 ns$$

$$\therefore f_{-3dB} = \frac{1}{2\pi \Sigma T_o} = 0.923 MHz$$

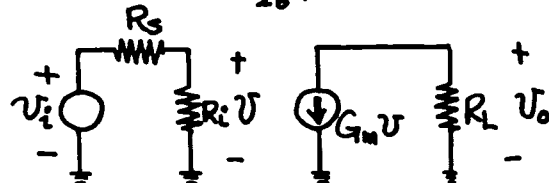
7.15

$$G_m = \frac{g_m}{1 + g_m R_E}$$

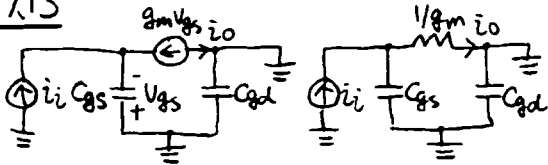
$$= \frac{1}{26} \frac{1}{1 + \frac{300}{26}} = 3.07 \times 10^{-3} A/V$$

$$R_i = r_\pi (1 + g_m R_E)$$

$$= 5.2 (1 + \frac{300}{26}) = 65.2K \Omega$$



7.13



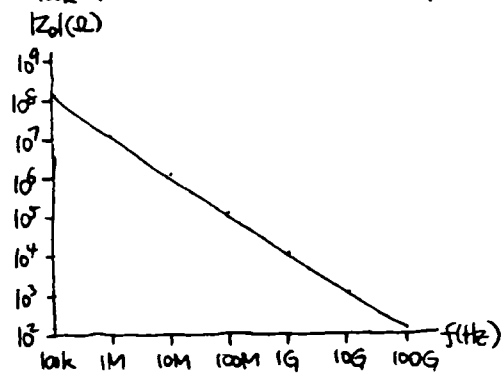
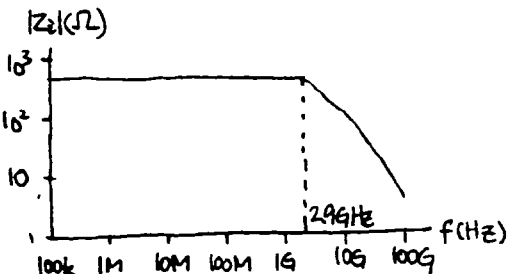
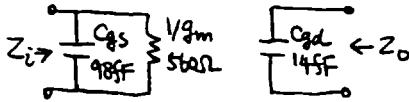
$$(a) \frac{i_o}{i_i} = \frac{\frac{1}{sC_{gs}}}{\frac{1}{sC_{gs}} + \frac{1}{g_m}} = \frac{1}{1 + s \frac{C_{gs}}{g_m}}$$

$$= \frac{1}{1 + s \frac{9.8 \times 10^{-15}}{1.8 \times 10^{-3}}} = \frac{1}{1 + s/(1.8 \times 10^9)}$$

$$f_{-3dB} = 2.9 GHz$$

$$(b) Z_i = \frac{1}{g_m} \parallel \frac{1}{sC_{gs}}$$

$$Z_o = \frac{1}{sC_{gd}}$$

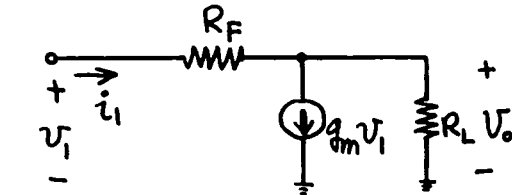
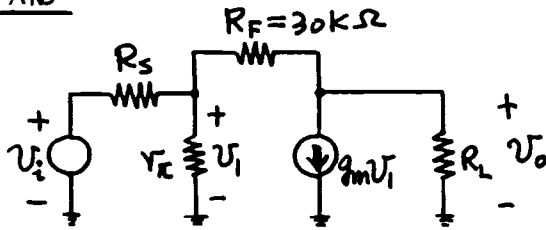


7-19

$$\begin{aligned}\frac{V_o}{V_i} &= -\frac{R_i}{R_s + R_i} G_m R_L \\ &= -\frac{65.2}{10 + 65.2} \times 3.07 \times 10^{-3} \times 5000 \\ &= -13.31\end{aligned}$$

$$\begin{aligned}R_{\mu o} &= R_x + R_L + G_m R_x R_L \\ R_x &= R_i \parallel R_s = 10 \parallel 65.2 = 8.67 \text{ k}\Omega \\ \therefore R_{\mu o} &= 8.67 + 5 + 3.07 \times 5 \times 8.67 \\ &= 147 \text{ k}\Omega \\ \therefore C_{\mu} R_{\mu o} &= 0.2 \times 147 = 29.4 \text{ ns} \\ C_{c s} R_{c s o} &= 1 \times 5 = 5 \text{ ns} \\ R_{\pi o} &= r_{\pi} \parallel \frac{R_s + r_b + R_E}{1 + g_m R_E} \\ &= 5.2 \text{ k} \parallel \frac{10 + 0.3}{1 + \frac{300}{26}} \text{ k} = 709 \Omega \\ C_{\pi} R_{\pi o} &= 10 \times 0.709 = 7.09 \text{ ns} \\ \therefore \Sigma T_o &= 29.4 + 5 + 7.09 = 41.49 \text{ ns} \\ \therefore f_{-3dB} &= \frac{1}{2\pi \Sigma T_o} = 3.84 \text{ MHz}\end{aligned}$$

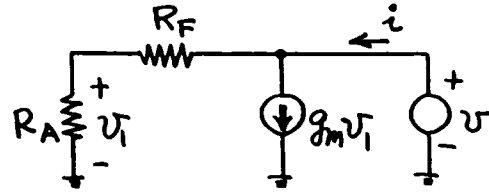
7.16



$$\begin{aligned}\frac{V_1 - V_o}{R_F} &= g_m V_1 + \frac{V_o}{R_L} \\ \therefore V_1 \left(\frac{1}{R_F} - g_m \right) &= V_o \left(\frac{1}{R_F} + \frac{1}{R_L} \right)\end{aligned}$$

$$\begin{aligned}\therefore \frac{V_o}{V_1} &= \frac{\frac{1}{R_F} - g_m}{\frac{1}{R_F} + \frac{1}{R_L}} \\ &= -\frac{1}{26} \frac{1}{\frac{1}{30} + \frac{1}{5}} \times 1000 \\ &= -\frac{1000}{26} \times \frac{30}{7} = -165 \\ \therefore i_1 &= \frac{V_1 - V_o}{R_F} = \frac{166 V_1}{R_F} \\ \therefore \frac{V_1}{i_1} &= \frac{R_F}{166} = 181 \Omega = R_1 \\ R_1 \parallel r_{\pi} &= 181 \parallel 5.2 \text{ k} = 175 \Omega \\ \therefore \frac{V_o}{V_i} &= \frac{175}{175 + R_s} \times \frac{V_o}{V_1} \\ &= -\frac{175}{175 + 10000} \times 165 = -2.84\end{aligned}$$

$$\begin{aligned}R_{\pi o} &= R_s \parallel r_{\pi} \parallel R_1 \\ &= 10 \text{ k} \parallel 5.2 \text{ k} \parallel 181 = 172 \Omega \\ \therefore C_{\pi} R_{\pi o} &= 10 \times 0.172 = 1.72 \text{ ns} \\ R_{\mu o} &= 30 \text{ k} \parallel 666 \text{ k} = 28.7 \text{ k}\Omega \\ \therefore C_{\mu} R_{\mu o} &= 0.2 \times 28.7 = 5.74 \text{ ns}\end{aligned}$$



$$\begin{aligned}R_A &= R_s \parallel r_{\pi} = 10 \text{ k} \parallel 5.2 \text{ k} = 3.42 \text{ k}\Omega \\ i &\approx g_m V_1 = g_m \frac{R_A}{R_A + R_F} V \\ \therefore \frac{V}{i} &= \frac{1}{g_m} \times \frac{R_A + R_F}{R_A} \\ &= 26 \times \frac{3.42 + 30}{3.42} = 254 \Omega = R_{c s o} \\ \therefore C_{c s} R_{c s o} &= 1 \times 0.254 = 0.25 \text{ ns} \\ \therefore \Sigma T_o &= (1.72 + 5.74 + 0.25) = 7.71 \text{ ns} \\ \therefore f_{-3dB} &= \frac{1}{2\pi \Sigma T_o} = 20.6 \text{ MHz}\end{aligned}$$

7.17

$$g_m = \sqrt{2k_n \frac{W}{L} I_D} = \sqrt{2 \times 60 \times 10^{-6} \times \frac{100}{2-2 \times 0.2-0} \times 500 \times 10^{-6}}$$

$$= 1.9 \times 10^{-3} \text{ A/V}$$

$$A_v = -g_m R_L = -1.9 \times 10^{-3} \times 5 \times 10^3 = -9.5$$

$$V_o = 10 - 0.5 \times 5 = 7.5 \text{ V}$$

$$C_{db} = A_D C_{j0} + P_D C_{jsw0}$$

$$= 5 \times 100 \times 0.4 + 100 \times 0.4$$

$$= 240 \text{ fF}$$

$$C_{db} = \frac{C_{db0}}{\sqrt{1 + \frac{V_{DB}}{V_0}}} = \frac{240}{\sqrt{1 + \frac{7.5}{0.6}}} = 65 \text{ fF}$$

$$R_L C_{db} = 5 \times 10^3 \times 65 \times 10^{-15} = 0.3 \text{ ns}$$

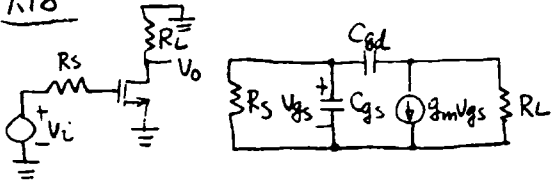
$$R_S [C_{gs} + C_{gd}(1 - A_v)]$$

$$= 10 \times 10^3 [89 + 14(1 + 9.5)] \times 10^{-15}$$

$$= 2.4 \text{ ns}$$

$$f_{-3dB} = \frac{1}{2\pi} \frac{1}{0.3 \text{ ns} + 2.4 \text{ ns}} = 59 \text{ MHz}$$

7.18



$$\frac{V_o}{V_i} = -g_m R_L = -1.8 \times 10^{-3} \times 5 \times 10^3 = -9$$

$$R_{gs0} = R_S = 10 \times 10^3 \Omega$$

$$C_{gs} R_{gs0} = 98 \times 10^{-15} \times 10 \times 10^3 = 9.8 \times 10^{-10} \text{ s}$$

$$R_{gd0} = R_S + R_L + g_m R_S R_L$$

$$= 10 \times 10^3 + 5 \times 10^3 + 1.8 \times 10^{-3} \times 10 \times 10^3 \times 5 \times 10^3$$

$$= 105 \times 10^3 \Omega = 105 \text{ k}\Omega$$

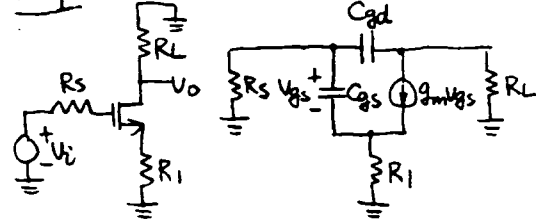
$$C_{gd} R_{gd0} = 14 \times 10^{-15} \times 105 \times 10^3 = 1.5 \times 10^{-9} \text{ s}$$

$$\Sigma T_0 = 9.8 \times 10^{-10} + 1.5 \times 10^{-9} = 2.5 \times 10^{-9} \text{ s}$$

$$f_{-3dB} = \frac{1}{2\pi \Sigma T_0} = \frac{1}{6.28 \times 2.5 \times 10^{-9}} = 6.4 \times 10^7 \text{ Hz}$$

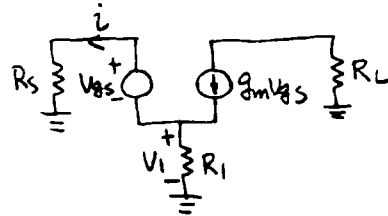
$$= 64 \text{ MHz}$$

7.19



$$\frac{V_o}{V_i} = -\frac{g_m}{1 + g_m R_1} R_L = -\frac{1.8 \times 10^{-3}}{1 + 1.8 \times 10^{-3} \times 900} \times 5 \times 10^3$$

$$= -3.4$$



$$i = \frac{V_{GS} + V_i}{R_S} = g_m V_{GS} - \frac{V_i}{R_1}$$

$$V_i = (R_S \parallel R_1) \left(g_m - \frac{1}{R_S} \right) V_{GS}$$

$$i = \frac{1}{R_S} \left[(R_S \parallel R_1) \left(g_m - \frac{1}{R_S} \right) + 1 \right] V_{GS} = \frac{1 + g_m R_1}{R_S + R_1} V_{GS}$$

$$R_{gs0} = \frac{R_S + R_1}{1 + g_m R_1} = \frac{10 \times 10^3 + 900}{1 + 1.8 \times 10^{-3} \times 900} = 4.2 \times 10^3 \Omega$$

$$C_{gs} R_{gs0} = 98 \times 10^{-15} \times 4.2 \times 10^3 = 4.1 \times 10^{-10} \text{ s}$$

$$R_{gd0} = R_S + R_L + \frac{g_m}{1 + g_m R_1} R_S R_L$$

$$= 10 \times 10^3 + 5 \times 10^3 + \frac{1.8 \times 10^{-3}}{1 + 1.8 \times 10^{-3} \times 900} \times 10 \times 10^3 \times 5 \times 10^3$$

$$= 49 \times 10^3 \Omega$$

$$C_{gd} R_{gd0} = 14 \times 10^{-15} \times 49 \times 10^3 = 6.9 \times 10^{-10} \text{ s}$$

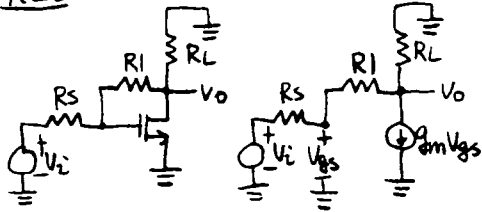
$$\Sigma T_0 = 4.1 \times 10^{-10} + 6.9 \times 10^{-10} = 1.1 \times 10^{-9} \text{ s}$$

$$f_{-3dB} = \frac{1}{2\pi \Sigma T_0} = \frac{1}{6.28 \times 1.1 \times 10^{-9}} = 1.4 \times 10^8 \text{ Hz}$$

$$= 140 \text{ MHz}$$

7-21

7.20



$$\frac{V_o}{R_L} + g_m V_{gs} + \frac{V_o - V_{gs}}{R_1} = 0$$

$$V_{gs} = \frac{V_o}{(R_L \parallel R_1) \left(\frac{1}{R_1} - g_m \right)} = V_o \frac{R_L + R_1}{R_L (1 - g_m R_1)}$$

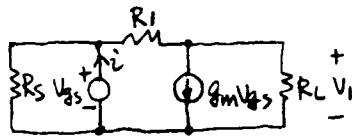
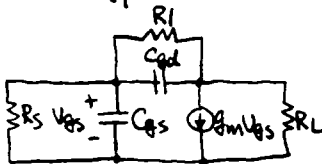
$$V_{gs} = \frac{R_s}{R_s + R_1} V_o + \frac{R_1}{R_s + R_1} V_i$$

$$\frac{R_L + R_1}{R_L (1 - g_m R_1)} V_o = \frac{R_s}{R_s + R_1} V_o + \frac{R_1}{R_s + R_1} V_i$$

$$\frac{V_o}{V_i} = \frac{\frac{R_1}{R_s + R_1}}{\frac{R_L + R_1}{R_L (1 - g_m R_1)} - \frac{R_s}{R_s + R_1}}$$

$$= \frac{\frac{R_1}{50 \times 10^3 + 10 \times 10^3}}{\frac{50 \times 10^3 + 50 \times 10^3}{5 \times 10^3 (1 - 1.8 \times 10^{-3} \times 5 \times 10^3)} - \frac{10 \times 10^3}{50 \times 10^3 + 10 \times 10^3}}$$

$$= -2.9$$



$$\frac{V_i}{R_L} + g_m V_{gs} = \frac{V_{gs} - V_i}{R_1}$$

$$V_i = (R_L \parallel R_1) \left(\frac{1}{R_1} - g_m \right) V_{gs}$$

$$i = \frac{V_{gs}}{R_s} + \frac{V_{gs} - V_i}{R_1} = V_{gs} \left[\frac{1}{R_s} + \frac{1 - (R_L \parallel R_1) \left(\frac{1}{R_1} - g_m \right)}{R_1} \right]$$

$$= V_{gs} \left[\frac{1}{R_s} + \frac{1 + g_m R_L}{R_L + R_1} \right]$$

$$R_{gs0} = \left[\frac{1}{R_s} + \frac{1 + g_m R_L}{R_L + R_1} \right]^{-1} = R_s \parallel \frac{R_L + R_1}{1 + g_m R_L}$$

$$= 10k \parallel \frac{5 \times 10^3 + 50 \times 10^3}{1 + 1.8 \times 10^{-3} \times 5 \times 10^3} = 3.5 \times 10^3 \Omega$$

$$C_{gs} R_{gs0} = 98 \times 10^{-15} \times 3.5 \times 10^3 = 3.4 \times 10^{-10} s$$

$$R_{gd0} = R_1 \parallel (R_s + R_L + g_m R_s R_L) = 50 \times 10^3 \parallel (10 \times 10^3 + 34 \times 10^3 \Omega)$$

$$= 34 \times 10^3 \Omega$$

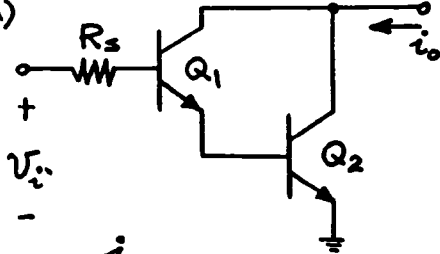
$$C_{gd} R_{gd0} = 14 \times 10^{-15} \times 34 \times 10^3 = 4.8 \times 10^{-10} s$$

$$\Sigma T_0 = 3.4 \times 10^{-10} + 4.8 \times 10^{-10} = 8.2 \times 10^{-10} s$$

$$f_{-3dB} = \frac{1}{2\pi \Sigma T_0} = \frac{1}{6.28 \times 8.2 \times 10^{-10}} = 1.9 \times 10^8 \text{ Hz}$$

$$= 190 \text{ MHz}$$

7.21
(a)



$$G_m = \frac{i_o}{V_i} \approx \frac{1}{2} g_{m2} = \frac{1}{2} \frac{1}{26}$$

$$= \frac{1}{52} \text{ A/V} \quad \text{— both circuits}$$

$$R_i \approx r_{\pi 1} (1 + g_{m1} r_{\pi 2}) = 2 r_{\pi 1} = 2 \frac{\beta}{g_{m1}}$$

$$= 2 \times 100 \times 2.6 \text{ k} = 520 \text{ k}\Omega$$

— both Circuits

$$\therefore \frac{v_o}{v_i} = - \frac{R_i}{R_i + R_s} G_m R_L$$

$$= - \frac{520}{620} \times \frac{1}{52} \times 3000$$

$$= -48.4 \quad \text{— both circuits}$$

(b) Darlington

$$R_{CS0} = R_L = 3 \text{ k}\Omega \quad \text{for } Q_1 \text{ and } Q_2$$

$$\therefore R_{CS0} (C_{s1} + C_{s2}) = 3 \times 2 = 6 \text{ ns}$$

$$R_{\pi 01} = r_{\pi 1} \parallel \frac{R_s + R_E}{1 + g_{m1} R_E} = r_{\pi 1} \parallel \frac{R_s + r_{\pi 2}}{1 + g_{m1} r_{\pi 2}}$$

$$= 260 \text{ k} \parallel \frac{102.6 \text{ k}}{2} = 42.9 \text{ k}\Omega$$

$$C_{\pi} + C_{\mu} = \frac{g_m}{2\pi f_T} = \frac{1}{26} \frac{1}{2\pi \times 500 \times 10^6}$$

$$= 12.2 \text{ pF} \quad \text{at } I_C = 1 \text{ mA}$$

$$\therefore C_{\pi} = 11.8 \text{ pF} \quad \text{at } I_C = 1 \text{ mA}$$

$$C_b = 9.8 \text{ pF}$$

$$\therefore C_{b1} = 0.1 \text{ pF}, \therefore C_{\pi 1} = 2.1 \text{ pF}$$

$$\therefore C_{\pi 1} R_{\pi 01} = 2.1 \times 42.9 = 90.1 \text{ ns}$$

$$R_{\mu 01} = R_x + R_L + G_m R_x R_L$$

$$R_x = R_i \parallel R_s = 520 \text{ k} \parallel 100 \text{ k} = 83.9 \text{ k}\Omega$$

$$\therefore R_{\mu 01} = 83.9 + 3 + \frac{1}{52} \times 3000 \times 83.9$$

$$= 4.93 \text{ M}\Omega$$

$$\therefore C_{\mu 1} R_{\mu 01} = 0.4 \times 4.93 \times 10^3 = 1972 \text{ ns}$$

$$C_{\pi 2} = 11.8 \text{ pF}$$

$$R_{\pi 02} = r_{\pi 2} \parallel \left(\frac{1}{g_{m1}} + \frac{R_s}{\beta_1} \right)$$

$$= 2.6 \text{ k} \parallel \left(2.6 \text{ k} + \frac{100 \text{ k}}{100} \right)$$

$$= 2.6 \text{ k} \parallel 3.6 \text{ k} = 1.51 \text{ k}\Omega$$

$$\therefore C_{\pi 2} R_{\pi 02} = 17.8 \text{ ns}$$

$$R_{\mu 02} = R_{\pi 02} + R_L + g_{m2} R_L R_{\pi 02}$$

$$= 1.51 + 3 + \frac{3000}{26} \times 1.51$$

$$= 179 \text{ k}\Omega$$

$$\therefore C_{\mu 2} R_{\mu 02} = 0.4 \times 179 = 71 \text{ ns}$$

$$\therefore \Sigma T_o = 6 + 90 + 1972 + 18 + 71$$

$$= 2157 \text{ ns}$$

$$\therefore f_{-3\text{dB}} = \frac{1}{2\pi \Sigma T_o} = 73.8 \text{ kHz}$$

Common-collector - Common emitter

$$R_{CS0} C_{s2} = 3 \text{ ns}$$

$$R_{CS0} C_{s1} = 0$$

$$C_{\pi 1} R_{\pi 01} = 90.1 \text{ ns}$$

$$C_{\pi 2} R_{\pi 02} = 17.8 \text{ ns}$$

$$C_{\mu 2} R_{\mu 02} = 71 \text{ ns}$$

$$R_{\mu 01} = R_i \parallel R_s = 83.9 \text{ k}\Omega$$

$$\therefore C_{\mu 1} R_{\mu 01} = 0.4 \times 83.9 = 33.6 \text{ ns}$$

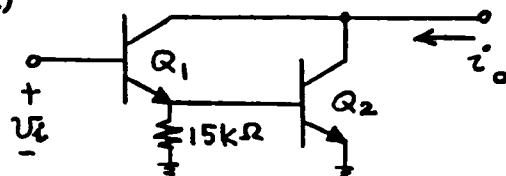
$$\therefore \Sigma T_o = 3 + 90.1 + 17.8 + 71 + 33.6$$

$$= 215.5 \text{ ns}$$

$$\therefore f_{-3\text{dB}} = \frac{1}{2\pi \Sigma T_o} = 738 \text{ kHz}$$

7.22

(a)



7-23

Effective value of $r_{\pi 2} = 15k \parallel 2.6k$

$$G_m = \frac{i_o}{v_i} \approx \frac{g_{m1} R_E}{g_{m1} R_E + 1} \times g_{m2}$$

$$R_E = 2.2k\Omega$$

$$\therefore G_m = \frac{\frac{0.05}{26} \times 2200}{1 + \frac{0.05}{26} \times 2200} \times \frac{1}{26}$$

$$= 31.2 \text{ mA/V} \text{ --- for both circuits}$$

$$R_i = r_{\pi 1} (1 + g_{m1} R_E)$$

$$= \frac{100 \times 26}{0.05} \left(1 + \frac{0.05}{26} \times 2200 \right) = 274k\Omega$$

$$\therefore \frac{v_o}{v_i} = - \frac{R_L}{R_i + R_s} G_m R_L$$

$$= - \frac{274}{274 + 100} \times 31.2 \times 10^{-3} \times 3000$$

$$= -68.6 \text{ --- for both circuits}$$

(b) $I_{C1} = 50\mu A \therefore C_{b1} = 0.5 \text{ pF}$

$$C_{\pi 1} = 2.5 \text{ pF}$$

Darlington

$$R_{C50} = R_L = 3k\Omega$$

$$\therefore R_{C50} (C_{cs1} + C_{cs2}) = 3 \times 2 = 6 \text{ ns}$$

$$R_{\pi 01} = r_{\pi 1} \parallel \frac{R_s + R_E}{1 + g_{m1} R_E}$$

$$= 52k \parallel \frac{102.2k}{1 + 4.27} = 14.1k\Omega$$

$$\therefore C_{\pi 1} R_{\pi 01} = 2.5 \times 14.1 = 35.3 \text{ ns}$$

$$R_{\mu 01} = R_x + R_L + G_m R_x R_L$$

$$R_x = R_i \parallel R_s = 274 \parallel 100 = 73.3k\Omega$$

$$\therefore R_{\mu 01} = 73.3 + 3 + 31.2 \times 73.3 \times 3$$

$$= 6.94 \text{ M}\Omega$$

$$\therefore C_{\mu 1} R_{\mu 01} = 0.4 \times 6940 = 2776 \text{ ns}$$

$$R_{\pi 02} = r_{\pi 2} \parallel \left(\frac{1}{g_{m1}} + \frac{R_s}{\beta_1} \right)$$

$$= 2.6k \parallel \left(520 + \frac{100k}{100} \right)$$

$$= 2.6k \parallel 1.52k = 959\Omega$$

$$\therefore C_{\pi 2} R_{\pi 02} = 11.8 \times 0.959 = 11.3 \text{ ns}$$

$$R_{\mu 02} = R_{\pi 02} + R_L + g_{m2} R_L R_{\pi 02}$$

$$= 0.959 + 3 + \frac{3000}{26} \times 0.959$$

$$= 114.6k\Omega$$

$$\therefore C_{\mu 2} R_{\mu 02} = 0.4 \times 114.6 = 45.8 \text{ ns}$$

$$\therefore \Sigma T_o = 6 + 35.3 + 2776 + 11.3 + 45.8$$

$$= 2874 \text{ ns}$$

$$\therefore f_{-3dB} = \frac{1}{2\pi \Sigma T_o} = 55.4 \text{ KHz}$$

Common-collector - Common emitter

$$R_{C50} C_{cs2} = 3 \text{ ns}$$

$$R_{C50} C_{cs1} = 0$$

$$C_{\pi 1} R_{\pi 01} = 35.3 \text{ ns}$$

$$C_{\pi 2} R_{\pi 02} = 11.3 \text{ ns}$$

$$C_{\mu 2} R_{\mu 02} = 45.8 \text{ ns}$$

$$R_{\mu 01} = R_i \parallel R_s = 274 \parallel 100 = 73.3k\Omega$$

$$\therefore C_{\mu 1} R_{\mu 01} = 0.4 \times 73.3 = 29.3 \text{ ns}$$

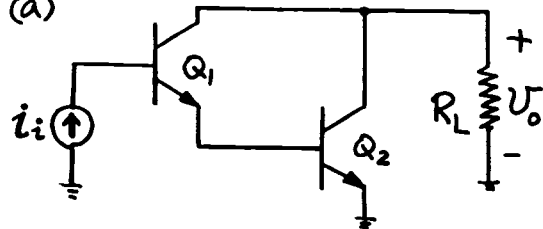
$$\therefore \Sigma T_o = 3 + 35.3 + 11.3 + 45.8 + 29.3$$

$$= 124.7 \text{ ns}$$

$$\therefore f_{-3dB} = \frac{1}{2\pi \Sigma T_o} = 1.28 \text{ MHz}$$

7.23

(a)



In both cases

$$\frac{v_o}{i_i} \approx -\beta_1 \beta_2 R_L = -100 \times 100 \times 3k = -30 \text{ M}\Omega$$

$$R_i = r_{\pi 1} (1 + g_{m1} r_{\pi 2}) = 520k\Omega$$

(b) Darlington

$$R_{C50} (C_{cs1} + C_{cs2}) = 6 \text{ ns}$$

7-24

$$R_{\pi 01} = r_{\pi 1} \parallel \frac{R_s + R_E}{1 + g_{m1} R_E} \quad R_s = \infty$$

$$= r_{\pi 1} = 260 \text{ k}\Omega$$

$$\therefore C_{\pi 1} R_{\pi 01} = 2.1 \times 260 = 546 \text{ ns}$$

$$R_{\mu 01} = R_x + R_L + g_{m1} R_x R_L$$

$$R_x = R_i \parallel R_s = R_i = 520 \text{ k}\Omega$$

$$\therefore R_{\mu 01} = 520 + 3 + \frac{3000}{52} \times 520$$

$$= 30.52 \text{ M}\Omega$$

$$\therefore C_{\mu 1} R_{\mu 01} = 0.4 \times 30520 = 12208 \text{ ns}$$

$$R_{\pi 02} = r_{\pi 2} \parallel \left(\frac{1}{g_{m1}} + \frac{R_s}{\beta_1} \right) \quad R_s = \infty$$

$$= r_{\pi 2} = 2.6 \text{ k}\Omega$$

$$\therefore C_{\pi 2} R_{\pi 02} = 11.8 \times 2.6 = 30.7 \text{ ns}$$

$$R_{\mu 02} = R_{\pi 02} + R_L + g_{m2} R_L R_{\pi 02}$$

$$= 2.6 + 3 + \frac{3000}{26} \times 2.6$$

$$= 305.6 \text{ k}\Omega$$

$$\therefore C_{\mu 2} R_{\mu 02} = 0.4 \times 305.6 = 122 \text{ ns}$$

$$\therefore \Sigma T_0 = (6 + 546 + 12208 + 30.7 + 122) \text{ ns}$$

$$= 12.9 \mu\text{s}$$

$$\therefore f_{-3dB} = \frac{1}{2\pi \Sigma T_0} = 12.3 \text{ KHz}$$

Common-Collector-Common emitter

$$R_{C50} C_{C52} = 3 \text{ ns}$$

$$R_{C50} C_{C51} = 0$$

$$C_{\pi 1} R_{\pi 01} = 546 \text{ ns}$$

$$C_{\pi 2} R_{\pi 02} = 30.7 \text{ ns}$$

$$C_{\mu 2} R_{\mu 02} = 122 \text{ ns}$$

$$R_{\mu 01} = R_i \parallel R_s = R_i = 520 \text{ k}\Omega$$

$$\therefore C_{\mu 1} R_{\mu 01} = 0.4 \times 520 = 208 \text{ ns}$$

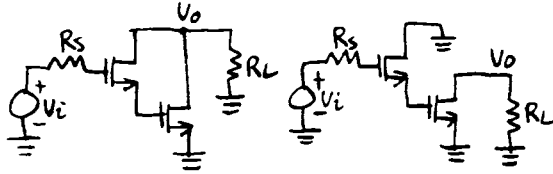
$$\therefore \Sigma T_0 = 3 + 546 + 30.7 + 122 + 208$$

$$= 910 \text{ ns}$$

$$\therefore f_{-3dB} = \frac{1}{2\pi \Sigma T_0} = 175 \text{ KHz}$$

7-25

7.24



(a) In both cases,

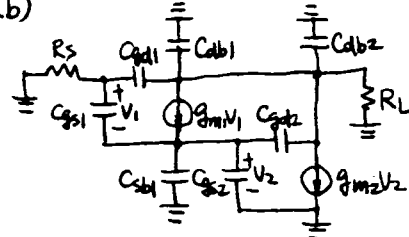
$$G_m = g_{m2} = \sqrt{2k_n' \left(\frac{W}{L}\right)_2 I_{D2}}$$

$$= \sqrt{2 \times 60 \times 10^{-6} \times \frac{100}{1.6} \times 10^{-3}}$$

$$= 2.7 \times 10^{-3} \text{ A/V}$$

$$\frac{V_o}{V_i} = -G_m R_L = -2.7 \times 10^{-3} \times 3 \times 10^3 = -8.1$$

(b)



For the "Darlington" stage,

 $C_{gs} = 89 \text{ fF}$, $C_{gd} = 14 \text{ fF}$.

$$g_{m1} = \sqrt{2 \times 60 \times 10^{-6} \times \frac{100}{1.6} \times 50 \times 10^{-6}} = 6.1 \times 10^{-4} \text{ A/V}$$

$$(C_{db1} + C_{db2}) R_L = (200 + 200) \times 10^{-15} \times 3 \times 10^3$$

$$= 1.2 \times 10^{-9} \text{ s}$$

$$C_{gs1} \frac{1}{g_{m1}} = 89 \times 10^{-15} \frac{1}{6.1 \times 10^{-4}} = 1.4 \times 10^{-10} \text{ s}$$

$$(C_{gs2} + C_{sb1}) \frac{1}{g_{m1}} = (89 + 180) \times 10^{-15} \frac{1}{6.1 \times 10^{-4}}$$

$$= 4.4 \times 10^{-10} \text{ s}$$

$$C_{gd1} (R_S + R_L + g_{m2} R_S R_L)$$

$$= 14 \times 10^{-15} (100 \times 10^3 + 3 \times 10^3 + 2.7 \times 10^{-3} \times 100 \times 10^3 \times 3 \times 10^3)$$

$$= 1.3 \times 10^{-8} \text{ s}$$

$$C_{gd2} \left(\frac{1}{g_{m1}} + R_L + g_{m2} \frac{1}{g_{m1}} R_L \right)$$

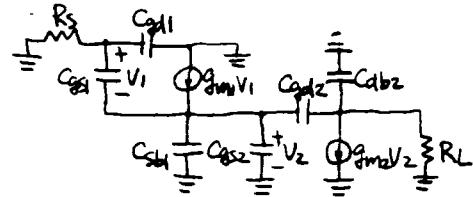
$$= 14 \times 10^{-15} \left(\frac{1}{6.1 \times 10^{-4}} + 3 \times 10^3 + \frac{2.7 \times 10^{-3}}{6.1 \times 10^{-4}} \times 3 \times 10^3 \right)$$

$$= 2.5 \times 10^{-10} \text{ s}$$

$$\Sigma T_0 = 1.5 \times 10^{-8} \text{ s}$$

$$f_{-3dB} = \frac{1}{2\pi \Sigma T_0} = \frac{1}{6.28 \times 1.5 \times 10^{-8}} = 1.0 \times 10^7 \text{ Hz}$$

$$= 10 \text{ MHz}$$



For the CD-CS stage,

$$C_{db2} R_L = 200 \times 10^{-15} \times 3 \times 10^3 = 6 \times 10^{-10} \text{ s}$$

$$C_{gs1} \frac{1}{g_{m1}} = 89 \times 10^{-15} \frac{1}{6.1 \times 10^{-4}} = 1.4 \times 10^{-10} \text{ s}$$

$$(C_{gs2} + C_{sb1}) \frac{1}{g_{m1}} = (89 + 180) \times 10^{-15} \frac{1}{6.1 \times 10^{-4}}$$

$$= 4.4 \times 10^{-10} \text{ s}$$

$$C_{gd1} R_S = 14 \times 10^{-15} \times 100 \times 10^3 = 1.4 \times 10^{-9} \text{ s}$$

$$C_{gd2} \left(\frac{1}{g_{m1}} + R_L + g_{m2} \frac{1}{g_{m1}} R_L \right)$$

$$= 14 \times 10^{-15} \left(\frac{1}{6.1 \times 10^{-4}} + 3 \times 10^3 + \frac{2.7 \times 10^{-3}}{6.1 \times 10^{-4}} \times 3 \times 10^3 \right)$$

$$= 2.5 \times 10^{-10} \text{ s}$$

$$\Sigma T_0 = 2.8 \times 10^{-9} \text{ s}$$

$$f_{-3dB} = 5.6 \times 10^7 \text{ Hz} = 56 \text{ MHz}$$

While the CD-CS stage has the same DC gain as the "Darlington" stage, the CD-CS stage has better frequency response.

7.25

$$(a) I_{C3} \approx \frac{10 - 0.6}{30} = 313 \mu A = I_{C2} = I_{C1}$$

$$Q_1 \quad V_{CB} = -10 + 0.6 = -9.4 V$$

$$\therefore C_{\mu 1} = \frac{C_{\mu 0}}{\sqrt{1 + \frac{|V_{CB}|}{\psi_0}}} = \frac{1}{\sqrt{1 + \frac{9.4}{0.55}}} = 0.24 \text{ pF}$$

$$V_{BS} = 20 - 0.6 = 19.4 V$$

$$\therefore C_{bs1} = \frac{2}{\sqrt{1 + \frac{19.4}{0.55}}} = 0.33 \text{ pF}$$

$$C_{bs1} + C_{\pi 1} + C_{\mu 1} = \frac{g_m}{2\pi f_T} = \frac{1}{2\pi \times 52 \times 4 \times 10^6} = 765 \text{ pF}$$

$$\therefore C_{\pi 1} = 764 \text{ pF} \text{ at } I_C = 0.5 \text{ mA}$$

$$C_{b1} = 761 \text{ pF} \text{ at } I_C = 0.5 \text{ mA}$$

$$\therefore \text{at } I_{C1} = 0.313 \text{ mA}$$

$$C_{b1} = 477 \text{ pF}$$

$$C_{\pi 1} = 480 \text{ pF}$$

$$r_{o1} = \frac{V_{A1}}{I_{C1}} = \frac{50}{0.313} = 160 \text{ k}\Omega$$

$$r_{\pi 1} = \frac{\beta_1}{g_m} = \frac{26 \times 50}{0.313} = 4.15 \text{ k}\Omega$$

$$Q_2 \quad V_{CB} = 9.4 V$$

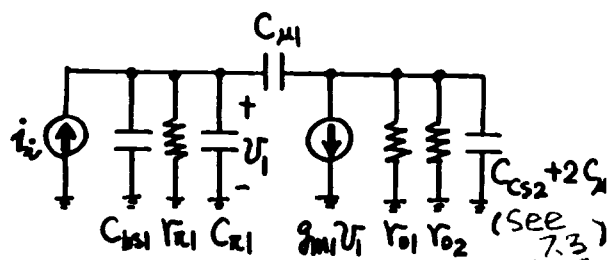
$$\therefore C_{\mu 2} = \frac{0.7}{\sqrt{1 + \frac{9.4}{0.55}}} = 0.16 \text{ pF}$$

$$V_{CS} = 10 V$$

$$\therefore C_{cs2} = \frac{2}{\sqrt{1 + \frac{10}{0.55}}} = 0.46 \text{ pF}$$

$$r_{o2} = \frac{V_{A2}}{I_{C2}} = \frac{120}{0.313}$$

$$= 383 \text{ k}\Omega$$



$$(C_{\pi 1} + C_{bs1})r_{\pi 1} = 480 \times 4.15 = 1.99 \mu s$$

$$R_{\mu 01} = r_{\pi 1} + r_{o1} + g_{m1}r_{\pi 1}r_{o1}$$

$$r_{o1} = r_{o1} \parallel r_{o2} = 160 \parallel 383 = 113 \text{ k}\Omega$$

$$\therefore R_{\mu 01} = 4.15 + 113 + \frac{26 \times 50}{26} \times 4150 \times 113 = 5.76 \text{ M}\Omega$$

$$\therefore C_{\mu 1}R_{\mu 01} = 0.24 \times 5.76 = 1.38 \mu s$$

$$r_{o1}(C_{cs2} + 2C_{\mu 2}) = 113 \times 0.78 = 88 \text{ ns}$$

$$\therefore \Sigma T_0 = 1.99 + 1.38 + 0.09 = 3.46 \mu s$$

$$\therefore f_{-3dB} = \frac{1}{2\pi \Sigma T_0} = 46 \text{ kHz}$$

$$(b) \frac{v_o}{i_i} = \beta_1 r_{o1} = 50 \times 113 = 5.65 \text{ M}\Omega$$

$$C_{\mu 1}R_{\mu 01} = 20.24 \times 5.76 = 116.6 \mu s$$

$$\therefore \Sigma T_0 = 1.99 + 116.6 + 0.09 = 118.7 \mu s$$

$$\therefore f_{-3dB} = \frac{1}{2\pi \Sigma T_0} = 1.34 \text{ kHz}$$

7-27

7.26

Iterate to find the bias current

Start with $V_{ov3} = 0$

$$I_3 = \frac{10 - V_t}{30k} = \frac{9}{30k} = 300 \mu A$$

$$V_{ov3} = \sqrt{\frac{2 \times 300}{60 \times 100 / (2 - 0.4 - 1)}} = 0.24 V$$

$$I_3 = \frac{10 - 1 - 0.24}{30k} = 290 \mu A$$

Still $V_{ov3} = 0.24 V$, so this is close enough.

$$\text{Now } V_{DS2} = 10V, V_{DS3} = 1.24V$$

$$\Delta V_{DS} = 8.8V,$$

$$I_1 = I_2 = 290 \left(1 + \frac{8.8}{100}\right) = 315 \mu A$$

$$g_{m1} = \sqrt{2 \times 20 \times (200 / 0.6) \times 315} = 2 \text{ mA/V}$$

$$r_{o1} = 50 / 315 = 160 k\Omega$$

$$g_{m2} = \sqrt{2 \times 60 \times (100 / 0.6) \times 315} = 2.5 \text{ mA/V}$$

$$r_{o2} = 100 / 315 = 320 k\Omega$$

$$g_{m3} = \sqrt{2 \times 60 \times (100 / 0.6) \times 290} = 2.4 \text{ mA/V}$$

$$r_{o3} = 100 / 290 = 340 k\Omega$$

$$(a) A = -\frac{1}{g_{m1}} g_{m1} (r_{o1} \parallel r_{o2}) = -160k \parallel 320k \\ = -110 k\Omega$$

$$C_{gs1} = \frac{2}{3} W L C_{ox} + W L_d C_{ox} \\ = \frac{2}{3} \times 200 \times (2 - 0.2 \times 2 - 1) \times 0.7 + \\ 200 \times 0.2 \times 0.7 \\ = 84 \text{ fF}$$

$$R(C_{gs1}) = \frac{1}{g_{m1}} = 500 \Omega$$

$$T_{gs1} = 0.084 \times 0.5 = 0.04 \text{ ns}$$

$$C_{db1} = A_0 C_{j0} + P_D C_{jsw0} = 5 \times 200 \times 0.2 + 200 \times 0.2 \\ = 240 \text{ fF}$$

$$C_{db2} = 5 \times 100 \times 0.4 + 100 \times 0.4 = 240 \text{ fF}$$

$$C_{db1} = C_{db2} = \frac{240}{\sqrt{1 + 10 / 0.6}} = 57 \text{ fF}$$

$$R(C_{db1}) = R(C_{db2}) = r_{o1} \parallel r_{o2} = 110 k\Omega$$

$$T_{db1-2} = 2 \times 0.057 \times 110 = 12.5 \text{ ns}$$

$$C_{gd2} = W L_d C_{ox} = 100 \times 0.2 \times 0.7 = 14 \text{ fF}$$

$$R(C_{gd2}) = \frac{1}{g_{m3}} \parallel r_{o3} \parallel 30k + r_{o1} \parallel r_{o2} \\ + g_{m2} \left[\frac{1}{g_{m3}} \parallel r_{o3} \parallel 30k \right] [r_{o1} \parallel r_{o2}] \\ \approx 2(r_{o1} \parallel r_{o2}) = 220 k\Omega$$

$$T_{gd2} = 0.014 \times 220 = 3 \text{ ns}$$

$$C_{gd1} = W L_d C_{ox} = 200 \times 0.2 \times 0.7 = 28 \text{ fF}$$

$$R(C_{gd1}) = \frac{1}{g_{m1}} + r_{o1} \parallel r_{o2} + g_{m1} \frac{1}{g_{m1}} (r_{o1} \parallel r_{o2}) \\ \approx 2(r_{o1} \parallel r_{o2}) = 220 k\Omega$$

$$T_{gd1} = 0.028 \times 220 = 6.2 \text{ ns}$$

$$f_{-3dB} = \frac{1}{2\pi \sum T_0} = \frac{1}{2\pi(0.04 + 12.5 + 3 + 6.2)} \\ = 7.3 \text{ MHz}$$

$$(b) C_{gd1} = 20 \text{ pF} + 28 \text{ fF} \approx 20 \text{ pF}$$

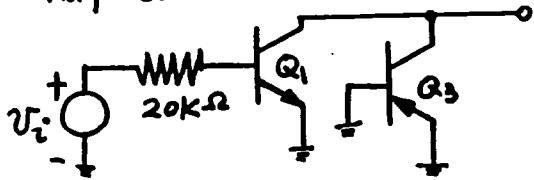
$$\text{Still } R(C_{gd1}) = 220k$$

$$T = 20 \times 220 = 4400 \text{ ns (dominant!)}$$

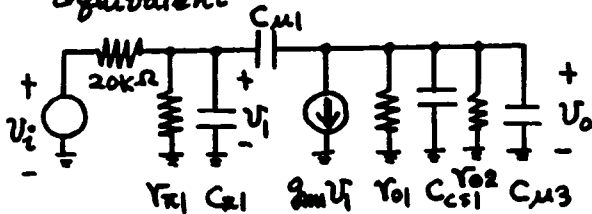
$$f_{-3dB} \approx \frac{1}{2\pi \times 4400 \text{ ns}} = 36 \text{ kHz}$$

7.27

Half-circuits (ac)



Equivalent



$$I_{C6} = \frac{9.4}{20} = 470 \mu A$$

$$I_{C5} = \frac{V_T}{R_E} \ln \frac{I_{C6}}{I_{C5}} = 2.6 \ln \frac{470}{I_{C5}} \mu A$$

$$= 10 \mu A$$

$$\therefore I_{C1} = I_{C3} = I_{C5}/2 = 5 \mu A$$

$$\frac{Q_1}{r_{O1}} = \frac{V_A}{I_{C1}} = \frac{120}{5} = 24 M\Omega$$

$$r_{\pi 1} = \frac{\beta}{g_{m1}} = 200 \times \frac{26}{0.005} = 1.04 M\Omega$$

$$C_{\mu 1} = \frac{0.7}{\sqrt{1 + \frac{5}{0.55}}} = 0.22 pF$$

$$C_{CS1} = \frac{2}{\sqrt{1 + \frac{15}{0.55}}} = 0.38 pF$$

$$C_{\pi 1} + C_{\mu 1} = \frac{2m}{2\pi f_T} = \frac{1}{2\pi \times 26 \times 500 \times 10^6}$$

$$= 12.2 pF \text{ at } 1mA$$

$$\therefore C_{\pi 1} = 12 pF \text{ at } 1mA$$

$$C_{\mu 1} = 9 pF \text{ at } 1mA$$

$$\approx 0 \text{ at } 5 \mu A$$

$$\therefore C_{\pi 1} = 3 pF \text{ at } 5 \mu A$$

$$\frac{Q_3}{r_{O3}} = \frac{50}{5} = 10 M\Omega$$

$$C_{\mu 3} = \frac{1}{\sqrt{1 + \frac{4.4}{0.55}}} = 0.33 pF$$

$$\frac{v_o}{v_i} = - \frac{r_{\pi 1}}{r_{\pi 1} + R_S} g_{m1} r_o$$

$$r_o = r_{O1} \parallel r_{O3} = 24 \parallel 10 = 7.06 M\Omega$$

$$\frac{v_o}{v_i} = - \frac{1.04}{1.06} \times \frac{0.005}{26} \times 7.06 \times 10^6$$

$$= -1332$$

$$R_{\pi O1} = r_{\pi 1} \parallel R_S = 1M \parallel 20k = 19.6 k\Omega$$

$$\therefore C_{\pi 1} R_{\pi O1} = 3 \times 19.6 = 59 ns$$

$$R_{\mu O1} = R_{\pi O1} + r_o + g_{m1} R_{\pi O1} r_o$$

$$R_{\mu O1} = 19.6k + 7.06M + \frac{0.005}{26} \times 19600 \times 7.06M$$

$$= 33.7 M\Omega$$

$$\therefore C_{\mu 1} R_{\mu O1} = 0.22 \times 33.7 = 7.41 \mu s$$

$$(C_{CS1} + C_{\mu 3}) r_o = 0.71 \times 7.06 = 5.0 \mu s$$

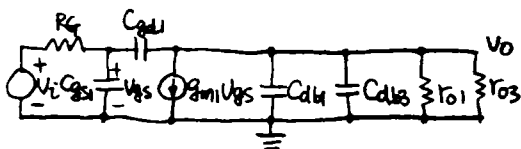
$$\therefore \Sigma T_o = 0.06 + 7.41 + 5 = 12.47 \mu s$$

$$\therefore f_{-3dB} = \frac{1}{2\pi \Sigma T_o} = 12.8 kHz$$

7-29

7.28

Half circuit



$$g_{m1} = \sqrt{2k_n' \left(\frac{W}{L}\right)_1 I_{D1}}$$

$$= \sqrt{2 \times 60 \times 10^{-6} \times \frac{100}{2 \times 0.2 \times 2 - 1} \times 0.5 \times 10^{-3}}$$

$$= 3.2 \times 10^{-3} \text{ A/V}$$

$$r_{o1} = \frac{1}{\lambda_n I_{D1}} = \frac{100}{0.5 \times 10^{-3}} = 2 \times 10^5 \Omega$$

$$r_{o3} = \frac{1}{|\lambda_p| I_{D3}} = \frac{50}{0.5 \times 10^{-3}} = 1 \times 10^5 \Omega$$

$$r_{o1} \parallel r_{o3} = 2 \times 10^5 \parallel 1 \times 10^5 = 6.7 \times 10^4$$

$$A = -g_{m1}(r_{o1} \parallel r_{o3}) = -3.2 \times 10^{-3} \times 6.7 \times 10^4$$

$$= -210$$

$$C_{gs1} = \frac{2}{3} W L_{eff} C_{ox} + W L_d C_{ox}$$

$$= \frac{2}{3} 100 \times (2 - 0.2 \times 2 - 1) \times 0.7 + 100 \times 0.2 \times 0.7$$

$$= 42 \text{ fF}$$

$$C_{gd1} = W L_d C_{ox} = 100 \times 0.2 \times 0.7 = 14 \text{ fF}$$

$$C_{db1} = A_D C_{j0} + P_D C_{jsw0} = 5 \times 100 \times 0.4 + 100 \times 0.4$$

$$= 240 \text{ fF}$$

$$C_{db3} = 5 \times 50 \times 0.2 + 50 \times 0.2 = 60 \text{ fF}$$

$$C_{db1} = \frac{C_{db1}}{\sqrt{1 + \frac{V_{DS}}{V_{D0}}}} = \frac{240}{\sqrt{1 + \frac{5}{0.6}}} = 78 \text{ fF}$$

$$C_{db3} = \frac{60}{\sqrt{1 + \frac{5}{0.6}}} = 20 \text{ fF}$$

$$C_{gs1} R_G = 42 \times 10^{-15} \times 20 \times 10^3 = 8.2 \times 10^{-10} \text{ s}$$

$$C_{gd1} [R_G + (r_{o1} \parallel r_{o3}) + g_{m1} R_G (r_{o1} \parallel r_{o3})]$$

$$= 14 \times 10^{-15} [20 \times 10^3 + 6.7 \times 10^4 + 3.2 \times 10^{-3} \times 20 \times 10^3 \times 6.7 \times 10^4]$$

$$= 6.1 \times 10^{-8} \text{ s}$$

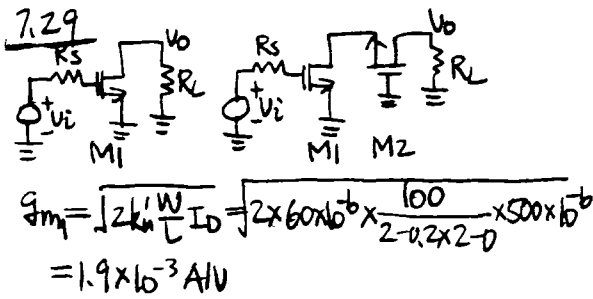
$$(C_{db1} + C_{db2})(r_{o1} \parallel r_{o3}) = (78 + 20) \times 10^{-15} \times 6.7 \times 10^4$$

$$= 6.6 \times 10^{-9} \text{ s}$$

$$\Sigma T_0 = 6.8 \times 10^{-8} \text{ s}$$

$$f_{-3dB} = \frac{1}{2\pi \Sigma T_0} = 2.3 \times 10^6 \text{ Hz} = 2.3 \text{ MHz}$$

7-30



$$g_{m1} = \sqrt{2k_n' \frac{W}{L} I_D} = \sqrt{2 \times 60 \times 10^{-6} \times \frac{100}{2 \times 0.2 \times 2 \times 10^{-8}} \times 500 \times 10^{-6}}$$

$$= 1.9 \times 10^{-3} \text{ A/V}$$

$$C_{gs} = \frac{2}{3} W L_{eff} C_{ox} + W L_d C_{ox}$$

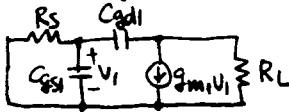
$$= \frac{2}{3} 100 \times 1.6 \times 0.7 + 100 \times 0.2 \times 0.7$$

$$= 89 \text{ fF}$$

$$C_{gd} = W L_d C_{ox} = 100 \times 0.2 \times 0.7 = 14 \text{ fF}$$

$$(a) \frac{V_o}{V_i} = -g_{m1} R_L = -1.9 \times 10^{-3} \times 20 \times 10^3 = -38$$

(b) The CS stage



$$C_{gs1} R_S = 89 \times 10^{-15} \times 10 \times 10^3 = 8.9 \times 10^{-10} \text{ s}$$

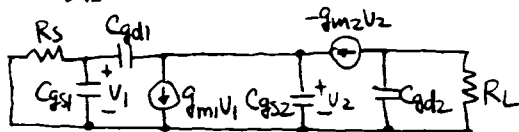
$$C_{gd1} (R_S + R_L + g_{m1} R_S R_L)$$

$$= 14 \times 10^{-15} (10 \text{ k} + 20 \text{ k} + 1.9 \text{ m} \times 10 \text{ k} \times 20 \text{ k})$$

$$= 5.7 \times 10^{-9} \text{ s}$$

$$f_{-3dB} = \frac{1}{2\pi (8.9 \times 10^{-10} + 5.7 \times 10^{-9})} = 2.4 \times 10^7 \text{ Hz}$$

$$t_r = \frac{0.35}{f_{-3dB}} = \frac{0.35}{2.4 \times 10^7} = 1.4 \times 10^{-8} \text{ s}$$



The cascode

$$C_{gs1} R_S = 89 \times 10^{-15} \times 10 \times 10^3 = 8.9 \times 10^{-10} \text{ s}$$

For M1, the load resistance is $\frac{1}{g_{m2}}$

$$C_{gd1} (R_S + \frac{1}{g_{m2}} + g_{m1} R_S \frac{1}{g_{m2}})$$

$$= C_{gd1} (2R_S + \frac{1}{g_{m2}})$$

$$= 14 \times 10^{-15} (2 \times 10 \times 10^3 + \frac{1}{1.9 \times 10^{-3}}) = 2.9 \times 10^{-10} \text{ s}$$

$$C_{gs2} \frac{1}{g_{m2}} = 89 \times 10^{-15} \frac{1}{1.9 \times 10^{-3}} = 4.7 \times 10^{-11} \text{ s}$$

$$C_{gd2} R_L = 14 \times 10^{-15} \times 20 \times 10^3 = 2.8 \times 10^{-10} \text{ s}$$

$$\Sigma T_0 = 1.5 \times 10^{-9} \text{ s}$$

$$f_{-3dB} = \frac{1}{2\pi \times 1.5 \times 10^{-9}} = 1 \times 10^8 \text{ Hz}$$

$$t_r = \frac{0.35}{1 \times 10^8} = 3.5 \times 10^{-9} \text{ s}$$

The cascode has a wider bandwidth.

7-31

$$\therefore R_{\mu 01} = 1.71 + 0.026 + \frac{1}{26} \times 26 \times 1.71 = 3.45 \text{ k}\Omega$$

$$\therefore C_{\mu 1} R_{\mu 01} = 0.4 \times 3.45 = 1.38 \text{ ns}$$

$$C_{cs1} R_{L1} = 1 \times 0.026 = 0.026 \text{ ns}$$

$$R_{\pi 02} = \frac{1}{g_{m2}} = 26 \Omega$$

$$\therefore C_{\pi 2} R_{\pi 02} = 11.8 \times 0.026 = 0.31 \text{ ns}$$

$$(C_{\mu 2} + C_{cs2}) R_{L2} = 1.4 \times 3 = 4.2 \text{ ns}$$

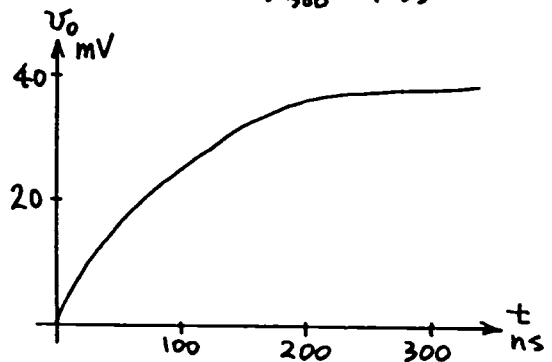
$$\therefore \Sigma T_0 = 20.2 + 1.38 + 0.03 + 0.31 + 4.2 = 26.1 \text{ ns}$$

$$\therefore f_{3dB} = 6.1 \text{ MHz}$$

This is 4 times higher than the Common-emitter stage, because Miller effect in Q_1 is eliminated.

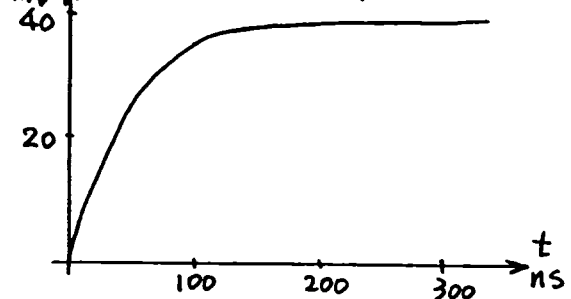
(c) Common-emitter

$$t_r(10-90\%) = \frac{0.35}{f_{3dB}} = \frac{0.35}{1.53} = 229 \text{ ns}$$



Cascode

$$t_r(10-90\%) = \frac{0.35}{6.1} = 57 \text{ ns}$$



7.30

$$C_{\pi} + C_{\mu} = \frac{g_m}{2\pi f_T} = \frac{1}{2\pi \times 26 \times 500 \times 10^6} = 12.2 \text{ pF at } I_C = 1 \text{ mA}$$

$$\therefore C_{\pi} = 11.8 \text{ pF}$$

$$r_{\pi} = \frac{\beta}{g_m} = 2.6 \text{ k}\Omega, r_o = \infty$$

(a) For each circuit

$$\begin{aligned} \frac{v_o}{v_i} &= - \frac{r_{\pi}}{r_{\pi} + R_s} g_m R_L \\ &= - \frac{2.6}{2.6 + 5} \frac{3000}{26} = -39.5 \end{aligned}$$

(b) Common emitter

$$R_{\pi 0} = r_{\pi} \parallel R_s = 2.6 \parallel 5 = 1.71 \text{ k}\Omega$$

$$\begin{aligned} R_{\mu 0} &= R_{\pi 0} + R_L + g_m R_L R_{\pi 0} \\ &= 1.71 + 3 + \frac{3000}{26} \times 1.71 \\ &= 202 \text{ k}\Omega \end{aligned}$$

$$C_{\pi} R_{\pi 0} = 11.8 \times 1.71 = 20.2 \text{ ns}$$

$$C_{\mu} R_{\mu 0} = 0.4 \times 202 = 80.8 \text{ ns}$$

$$C_{cs} R_L = 1 \times 3 = 3 \text{ ns}$$

$$\therefore \Sigma T_0 = 20.2 + 80.8 + 3 = 104 \text{ ns}$$

$$\text{Cascode } \therefore f_{3dB} = \frac{1}{2\pi \Sigma T_0} = 1.53 \text{ MHz}$$

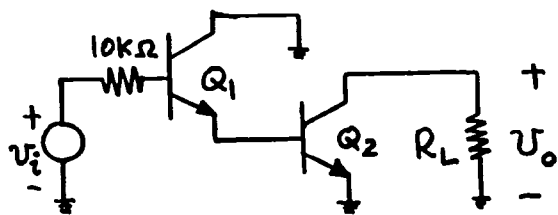
$$C_{\pi 1} R_{\pi 01} = 20.2 \text{ ns}$$

$$R_{\mu 01} = R_{\pi 01} + R_{L1} + g_{m1} R_{L1} R_{\pi 01}$$

$$R_{L1} = \frac{1}{g_{m2}} = 26 \Omega$$

7.31

(a) Half-circuit



$$Q_1 \quad I_{C1} = I_0 + I_{B2} = 12.5 \mu\text{A}$$

$$r_{\pi 1} = 200 \times \frac{26}{0.013} = 416 \text{ k}\Omega$$

$$C_{\mu 1} = \frac{0.5}{\sqrt{1 + \frac{6}{0.55}}} = 0.14 \text{ pF}$$

$$C_{\pi 1} + C_{\mu 1} = \frac{g_{m1}}{2\pi f_T} = \frac{1}{2\pi \times 13 \times 500 \times 10^6}$$

$$= 24.5 \text{ pF at } 2 \text{ mA}$$

$$\therefore C_{b1} = 20.4 \text{ pF at } 2 \text{ mA}$$

$$= 0.1 \text{ pF at } 12.5 \mu\text{A}$$

$$\therefore C_{\pi 1} = 4.1 \text{ pF}$$

$$Q_2 \quad I_{C2} = 0.5 \text{ mA}$$

$$r_{\pi 2} = 200 \times \frac{26}{0.5} = 10.4 \text{ k}\Omega$$

$$V_{C2} = 6 - 5 \times \frac{1}{2} = 3.5 \text{ V}$$

$$\therefore C_{\mu 2} = \frac{0.5}{\sqrt{1 + \frac{4.1}{0.55}}} = 0.17 \text{ pF}$$

$$C_{cs2} = \frac{1}{\sqrt{1 + \frac{9.5}{0.55}}} = 0.23 \text{ pF}$$

$$C_{b2} = 5.1 \text{ pF at } 0.5 \text{ mA}$$

$$\therefore C_{\pi 2} = 9.1 \text{ pF}$$

$$R_i = r_{\pi 1} (1 + g_{m1} r_{\pi 2})$$

$$= 416 \left(1 + \frac{0.0125}{26} \times 10400 \right) \text{ k}\Omega$$

$$= 2.5 \text{ M}\Omega$$

$$\frac{v_o}{v_i} = - \frac{R_i}{R_i + R_s} \frac{g_{m1} r_{\pi 2}}{1 + g_{m1} r_{\pi 2}} g_{m2} R_L$$

$$\frac{v_o}{v_i} = - \frac{2.5}{2.51} \frac{5}{6} \frac{0.5}{26} \times 5000$$

$$= -79.8$$

$$(b) R_{\mu 01} = R_s \parallel R_i \approx 10 \text{ k}\Omega$$

$$\therefore C_{\mu 1} R_{\mu 01} = 0.14 \times 10 = 1.4 \text{ ns}$$

$$R_{\pi 01} = r_{\pi 1} \parallel \frac{R_s + R_E}{1 + g_{m1} R_E} = r_{\pi 1} \parallel \frac{R_s + r_{\pi 2}}{1 + g_{m1} r_{\pi 2}}$$

$$= 416 \text{ k}\Omega \parallel \frac{20.4 \text{ k}\Omega}{1 + \frac{0.0125}{26} \times 10400}$$

$$= 416 \text{ k}\Omega \parallel 3.4 \text{ k}\Omega = 3.37 \text{ k}\Omega$$

$$\therefore C_{\pi 1} R_{\pi 01} = 4.1 \times 3.37 = 13.8 \text{ ns}$$

$$R_{\pi 02} = r_{\pi 2} \parallel \left(\frac{1}{g_{m1}} + \frac{R_s}{\beta_1} \right)$$

$$= 10.4 \text{ k}\Omega \parallel \left(\frac{26}{0.0125} + \frac{10000}{200} \right)$$

$$= 10.4 \text{ k}\Omega \parallel 2.13 \text{ k}\Omega = 1.77 \text{ k}\Omega$$

$$\therefore C_{\pi 2} R_{\pi 02} = 9.1 \times 1.77 = 16.1 \text{ ns}$$

$$R_{\mu 02} = R_{\pi 02} + R_L + g_{m2} R_{\pi 02} R_L$$

$$= 1.77 \text{ k}\Omega + 5 \text{ k}\Omega + \frac{0.5}{26} \times 1770 \times 5 \text{ k}\Omega$$

$$= 177 \text{ k}\Omega$$

$$\therefore C_{\mu 2} R_{\mu 02} = 0.17 \times 177 = 30.1 \text{ ns}$$

$$C_{cs2} R_L = 0.23 \times 5 = 1.15 \text{ ns}$$

$$\therefore \Sigma T_0 = 1.4 + 13.8 + 16.1 + 30.1 + 1.2$$

$$= 62.6 \text{ ns}$$

$$\therefore f_{-3\text{dB}} = \frac{1}{2\pi \Sigma T_0} = 2.54 \text{ MHz}$$

```

AMPLIFIER, RB=0
VCC 1 0 6V
VEE 2 0 -6V
RL1 1 3 5K
RL2 1 4 5K
Q1 1 9 5 NPN
Q2 3 5 7 NPN
Q3 4 6 7 NPN
Q4 1 10 6 NPN
IBIAS1 5 2 100A
IBIAS4 6 2 100A
IBIAS23 7 2 1MA
RS1 8 9 10K
RS4 10 0 10K
VI 8 0 0V AC
.PLOT AC VDB(3,4)
.PLOT AC VP(3,4)
.AC DEC 10 10K 100MEG
.MODEL NPN NPN IS=1E-16A BF=200 RB=0
+ CJC=4PF CJC=0.5PF CJS=2PF TF=208PS
+ MJE=0.5 MJC=0.5 MJS=0.5 VJE=0.55 VJC=0.55 VJS=0.55
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

```

***** OPERATING POINT INFORMATION          TWOM= 27.000 TEMP= 27.000
+0:1      = 6.000E+00 0:2      =-6.000E+00 0:3      = 3.512E+00
+0:4      = 3.512E+00 0:5      =-6.613E-01 0:6      =-6.613E-01
+0:7      =-1.417E+00 0:8      = 0.          0:9      =-6.212E-04
+0:10     =-6.212E-04

```

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**** BIPOLAR JUNCTION TRANSISTORS
ELEMENT 0:Q1      0:Q2      0:Q3      0:Q4
MODEL   0:NPN     0:NPN     0:NPN     0:NPN
IB       6.213E-08 2.488E-06 2.488E-06 6.213E-08
IC       1.243E-05 4.975E-04 4.975E-04 1.243E-05
VBE      6.607E-01 7.562E-01 7.562E-01 6.607E-01
VCE      6.661E+00 4.929E+00 4.929E+00 6.661E+00
VBC      -6.000E+00 -4.173E+00 -4.173E+00 -6.000E+00
VS       -6.000E+00 -3.512E+00 -3.512E+00 -6.000E+00
POWER    8.281E-05 2.455E-03 2.455E-03 8.281E-05
BETAD    2.000E+02 2.000E+02 2.000E+02 2.000E+02
GM       4.804E-04 1.924E-02 1.924E-02 4.804E-04
RPI      4.163E+05 1.039E+04 1.039E+04 4.163E+05
RX       0.         0.         0.         0.
RO       6.000E+16 4.173E+16 4.173E+16 6.000E+16
CPI      9.724E-12 1.461E-11 1.461E-11 9.724E-12
CMU      1.449E-13 1.706E-13 1.706E-13 1.449E-13
CBX      0.         0.         0.         0.
CCS      5.795E-13 7.359E-13 7.359E-13 5.795E-13
BETAMC   2.000E+02 2.000E+02 2.000E+02 2.000E+02
FT       7.747E+06 2.071E+08 2.071E+08 7.747E+06

```

```

***** AC ANALYSIS          TWOM= 27.000 TEMP= 27.000

```

FREQ	VDB(3,4)	0.	2.000E+01	4.000E+01	6.000E+01
9.999E+03	3.80E+01				A
1.258E+04	3.80E+01				A
1.584E+04	3.80E+01				A
1.995E+04	3.80E+01				A
2.511E+04	3.80E+01				A
3.162E+04	3.80E+01				A
3.981E+04	3.80E+01				A
5.011E+04	3.80E+01				A
6.309E+04	3.80E+01				A
7.943E+04	3.80E+01				A
1.000E+05	3.80E+01				A
1.258E+05	3.80E+01				A
1.584E+05	3.80E+01				A
1.995E+05	3.80E+01				A
2.511E+05	3.80E+01				A
3.162E+05	3.81E+01				A
3.981E+05	3.81E+01				A
5.011E+05	3.81E+01				A
6.309E+05	3.81E+01				A
7.943E+05	3.82E+01				A
1.000E+06	3.83E+01				A
1.258E+06	3.83E+01				A
1.584E+06	3.80E+01				A
1.995E+06	3.70E+01				A
2.511E+06	3.50E+01				A
3.162E+06	3.20E+01				A
3.981E+06	2.86E+01				A
5.011E+06	2.51E+01				A
6.309E+06	2.17E+01				A
7.943E+06	1.85E+01				A
1.000E+07	1.56E+01				A
1.258E+07	1.29E+01				A
1.584E+07	1.03E+01				A
1.995E+07	7.88E+00				A
2.511E+07	5.48E+00				A
3.162E+07	3.08E+00				A
3.981E+07	6.18E-01				A
5.011E+07	-1.97E+00				A
6.309E+07	-4.73E+00				A
7.943E+07	-7.70E+00				A
1.000E+08	-1.09E+01				A

FREQ	VP(3,4)	0.	5.000E+01	1.000E+02	1.500E+02	2.000E+02
9.999E+03	1.79E+02					A
1.258E+04	1.79E+02					A
1.584E+04	1.79E+02					A
1.995E+04	1.79E+02					A
2.511E+04	1.79E+02					A
3.162E+04	1.79E+02					A
3.981E+04	1.78E+02					A
5.011E+04	1.78E+02					A
6.309E+04	1.78E+02					A
7.943E+04	1.77E+02					A
1.000E+05	1.77E+02					A
1.258E+05	1.76E+02					A
1.584E+05	1.75E+02					A
1.995E+05	1.74E+02					A
2.511E+05	1.73E+02					A
3.162E+05	1.71E+02					A
3.981E+05	1.69E+02					A
5.011E+05	1.66E+02					A
6.309E+05	1.62E+02					A
7.943E+05	1.57E+02					A
1.000E+06	1.50E+02					A
1.258E+06	1.40E+02					A
1.584E+06	1.27E+02					A
1.995E+06	1.10E+02					A
2.511E+06	9.23E+01					A
3.162E+06	7.75E+01					A
3.981E+06	6.76E+01					A
5.011E+06	6.20E+01					A
6.309E+06	5.96E+01					A
7.943E+06	5.92E+01					A
1.000E+07	5.98E+01					A
1.258E+07	6.07E+01					A
1.584E+07	6.13E+01					A
1.995E+07	6.12E+01					A
2.511E+07	6.01E+01					A
3.162E+07	5.79E+01					A
3.981E+07	5.45E+01					A
5.011E+07	5.02E+01					A
6.309E+07	4.50E+01					A
7.943E+07	3.93E+01					A
1.000E+08	3.35E+01					A

```

*****
AMPLIFIER, RB=200
VCC 1 0 6V
VEE 2 0 -6V
RL1 1 3 5K
RL2 1 4 5K
Q1 1 9 5 NPN
Q2 3 5 7 NPN
Q3 4 6 7 NPN
Q4 1 10 6 NPN
IBIAS1 5 2 100A
IBIAS4 6 2 100A
IBIAS23 7 2 1MA
RS1 8 9 10K
RS4 10 0 10K
VI 8 0 0V AC
.PLOT AC VDB(3,4)
.PLOT AC VP(3,4)
.AC DEC 10 10K 100MEG
.MODEL NPN NPN IS=1E-16A BF=200 RB=200
+ CJC=4PF CJC=0.5PF CJS=2PF TF=208PS
+ MJE=0.5 MJC=0.5 MJS=0.5 VJE=0.55 VJC=0.55 VJS=0.55
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

```

***** OPERATING POINT INFORMATION          TWOM= 27.000 TEMP= 27.000

```

```

+0:1      = 6.000E+00 0:2      =-6.000E+00 0:3      = 3.512E+00
+0:4      = 3.512E+00 0:5      =-6.613E-01 0:6      =-6.613E-01
+0:7      =-1.418E+00 0:8      = 0.          0:9      =-6.212E-04
+0:10     =-6.212E-04

```

```

**** BIPOLAR JUNCTION TRANSISTORS

```

ELEMENT	0:Q1	0:Q2	0:Q3	0:Q4
MODEL	0:NPN	0:NPN	0:NPN	0:NPN
IB	6.213E-08	2.488E-06	2.488E-06	6.213E-08
IC	1.243E-05	4.975E-04	4.975E-04	1.243E-05
VBE	6.607E-01	7.566E-01	7.566E-01	6.607E-01
VCE	6.661E+00	4.930E+00	4.930E+00	6.661E+00
VBC	-6.000E+00	-4.173E+00	-4.173E+00	-6.000E+00
VS	-6.000E+00	-3.512E+00	-3.512E+00	-6.000E+00
POWER	8.281E-05	2.455E-03	2.455E-03	8.281E-05
BETAD	2.000E+02	2.000E+02	2.000E+02	2.000E+02
GM	4.804E-04	1.924E-02	1.924E-02	4.804E-04
RPI	4.163E+05	1.039E+04	1.039E+04	4.163E+05
RX	2.000E+02	2.000E+02	2.000E+02	2.000E+02
RO	6.000E+16	4.174E+16	4.174E+16	6.000E+16
CPI	9.724E-12	1.461E-11	1.461E-11	9.724E-12

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```

CMU      1.449E-13  1.706E-13  1.706E-13  1.449E-13
CBX      0.         0.         0.         0.
CCS      5.795E-13  7.359E-13  7.359E-13  5.795E-13
BETAC    2.000E+02  2.000E+02  2.000E+02  2.000E+02
FT       7.747E+06  2.071E+08  2.071E+08  7.747E+06

```

```

***** AC ANALYSIS          THOM= 27.000 TEMP= 27.000

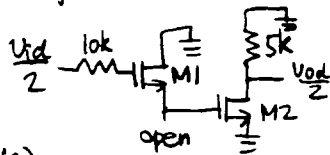
```

FREQ (A)	VDB(3,4)					
	-2.000E+01	0.	2.000E+01	4.000E+01	6.000E+01	
9.999E+03	3.79E+01					
1.258E+04	3.79E+01	+	+	+	+	A+
1.584E+04	3.79E+01	+	+	+	+	A+
1.995E+04	3.79E+01	+	+	+	+	A+
2.511E+04	3.79E+01	+	+	+	+	A+
3.162E+04	3.79E+01	+	+	+	+	A+
3.981E+04	3.79E+01	+	+	+	+	A+
5.011E+04	3.79E+01	+	+	+	+	A+
6.309E+04	3.79E+01	+	+	+	+	A+
7.943E+04	3.79E+01	+	+	+	+	A+
1.000E+05	3.79E+01					
1.258E+05	3.79E+01	+	+	+	+	A+
1.584E+05	3.79E+01	+	+	+	+	A+
1.995E+05	3.79E+01	+	+	+	+	A+
2.511E+05	3.79E+01	+	+	+	+	A+
3.162E+05	3.79E+01	+	+	+	+	A+
3.981E+05	3.79E+01	+	+	+	+	A+
5.011E+05	3.79E+01	+	+	+	+	A+
6.309E+05	3.80E+01	+	+	+	+	A+
7.943E+05	3.80E+01	+	+	+	+	A+
1.000E+06	3.80E+01					
1.258E+06	3.80E+01	+	+	+	+	A+
1.584E+06	3.76E+01	+	+	+	+	A+
1.995E+06	3.65E+01	+	+	+	+	A+
2.511E+06	3.44E+01	+	+	+	+	A+
3.162E+06	3.15E+01	+	+	+	+	A+
3.981E+06	2.81E+01	+	+	+	+	A+
5.011E+06	2.47E+01	+	+	+	+	A+
6.309E+06	2.13E+01	+	+	+	+	A+
7.943E+06	1.82E+01	+	+	+	+	A+
1.000E+07	1.52E+01					
1.258E+07	1.25E+01	+	+	A	+	+
1.584E+07	9.97E+00	+	+	A	+	+
1.995E+07	7.53E+00	+	+	A	+	+
2.511E+07	5.13E+00	+	+	A	+	+
3.162E+07	2.73E+00	+	+	A	+	+
3.981E+07	2.73E+01	+	+	A	+	+
5.011E+07	-2.31E+00	+	+	A	+	+
6.309E+07	-5.07E+00	+	+	A	+	+
7.943E+07	-8.04E+00	+	+	A	+	+
1.000E+08	-1.12E+01					

FREQ (A)	VP(3,4)					
	0.	5.000E+01	1.000E+02	1.500E+02	2.000E+02	
9.999E+03	1.79E+02					A-
1.258E+04	1.79E+02	+	+	+	+	A
1.584E+04	1.79E+02	+	+	+	+	A
1.995E+04	1.79E+02	+	+	+	+	A
2.511E+04	1.79E+02	+	+	+	+	A
3.162E+04	1.79E+02	+	+	+	+	A
3.981E+04	1.78E+02	+	+	+	+	A
5.011E+04	1.78E+02	+	+	+	+	A
6.309E+04	1.78E+02	+	+	+	+	A
7.943E+04	1.77E+02	+	+	+	+	A
1.000E+05	1.77E+02					
1.258E+05	1.76E+02	+	+	+	+	A
1.584E+05	1.75E+02	+	+	+	+	A
1.995E+05	1.74E+02	+	+	+	+	A
2.511E+05	1.72E+02	+	+	+	+	A
3.162E+05	1.71E+02	+	+	+	+	A
3.981E+05	1.68E+02	+	+	+	+	A
5.011E+05	1.65E+02	+	+	+	+	A
6.309E+05	1.61E+02	+	+	+	+	A
7.943E+05	1.56E+02	+	+	+	+	A
1.000E+06	1.48E+02					
1.258E+06	1.39E+02	+	+	+	+	A
1.584E+06	1.25E+02	+	+	+	+	A
1.995E+06	1.08E+02	+	+	+	+	A
2.511E+06	9.17E+01	+	+	+	+	A
3.162E+06	7.5E+01	+	+	+	+	A
3.981E+06	6.79E+01	+	+	+	+	A
5.011E+06	6.25E+01	+	+	+	+	A
6.309E+06	6.00E+01	+	+	+	+	A
7.943E+06	5.95E+01	+	+	+	+	A
1.000E+07	6.01E+01					
1.258E+07	6.09E+01	+	+	+	+	A
1.584E+07	6.14E+01	+	+	+	+	A
1.995E+07	6.12E+01	+	+	+	+	A
2.511E+07	6.20E+01	+	+	+	+	A
3.162E+07	5.77E+01	+	+	+	+	A
3.981E+07	5.42E+01	+	+	+	+	A
5.011E+07	4.97E+01	+	+	+	+	A
6.309E+07	4.44E+01	+	+	+	+	A
7.943E+07	3.96E+01	+	+	+	+	A
1.000E+08	3.26E+01					

7.32

Half circuit



(a)

$$g_{m1} = \sqrt{2 \times 60 \times \frac{100}{1.6}} \times 10 = 270 \mu\text{A/V}$$

$$g_{m2} = \sqrt{2 \times 60 \times \frac{100}{1.6}} \times 500 = 1.9 \text{ mA/V}$$

M1 is a source follower with a perfect current source, $\lambda = 0$ and no body effect.

Its gain is 1.

$$\frac{v_{od}}{v_{id}} = -g_{m2} \times 5k = -9.6$$

(b) Since M1 is an ideal source follower, its gain is 1. Therefore, the voltage across C_{gs1} does not change. So ignore C_{gs1} .

$$C_{gd1} = W L_d C_{ox} = 100 \times 0.2 \times 0.7 = 14 \text{ fF}$$

$$R(C_{gd1}) = 10k\Omega$$

$$T_{gd1} = 0.014 \times 10 = 0.14 \text{ ns}$$

$$C_{sbo1} = A_0 C_{j0} + P_0 C_{jsw0} \\ = 5 \times 100 \times 0.4 + 100 \times 0.4 = 240 \text{ fF}$$

$$V_{s1} = 0 - V_E - V_{ov1}$$

$$V_{ov1} = \sqrt{\frac{2 \times 10}{60 \times (100/1.6)}} = 0.07 \text{ V}$$

$$V_{s1} = -1.07 \text{ V}$$

$$C_{sb1} = \frac{C_{sbo1}}{\sqrt{1 + \frac{V_{DB}}{\Phi_0}}} = \frac{240}{\sqrt{1 + \frac{-1.07 - (-6)}{0.6}}} = 80 \text{ fF}$$

$$R(C_{sb1}) = \frac{1}{g_{m1}} = 3.7k\Omega$$

$$T_{sb1} = 0.08 \times 3.7 = 0.3 \text{ ns}$$

$$C_{gs2} = \frac{2}{3} W L_{eff} C_{ox} + W L_d C_{ox} \\ = \frac{2}{3} \times 100 \times 1.6 \times 0.7 + 100 \times 0.2 \times 0.7 \\ = 90 \text{ fF}$$

$$R(C_{gs2}) = \frac{1}{g_{m1}} = 3.7k\Omega$$

$$T_{gs2} = 0.09 \times 3.7 = 0.33 \text{ ns}$$

$$C_{db2} = A_0 C_{j0} + P_0 C_{jsw0}$$

$$= 5 \times 100 \times 0.4 + 100 \times 0.4 = 240 \text{ fF}$$

$$V_{D2} = 6 - 5k \times 0.5 \text{ mA} = 3.5 \text{ V}$$

$$C_{db2} = \frac{C_{db02}}{\sqrt{1 + \frac{V_{DB}}{\Phi_0}}} = \frac{240}{\sqrt{1 + \frac{3.5 - (-6)}{0.6}}} = 60 \text{ fF}$$

$$R(C_{db2}) = 5k\Omega$$

$$T_{db2} = 0.06 \times 5 = 0.3 \text{ ns}$$

$$C_{gd2} = W L_d C_{ox} = 100 \times 0.2 \times 0.7 = 14 \text{ fF}$$

$$R(C_{gd2}) = \frac{1}{g_{m1}} + 5k + g_{m2} \frac{1}{g_{m1}} 5k \\ = \frac{1}{270 \times 10^{-6}} + 5 \times 10^3 + \frac{1.9 \times 10^{-3}}{270 \times 10^{-6}} \times 5 \times 10^3 \\ = 44 \times 10^3 \Omega$$

$$T_{gd2} = 0.014 \times 44 = 0.62 \text{ ns}$$

$$f_{-3dB} = \frac{1}{2\pi} \frac{1}{0.14 + 0.3 + 0.33 + 0.3 + 0.62} = 94 \text{ MHz}$$

```

AMPLIFIER
VDD 1 0 6V
VSS 2 0 -6V
RL1 1 3 5K
RL2 1 4 5K
M1 1 9 5 5 CMOSN W=100U L=2U AD=500E-12 PD=100U
M2 3 5 7 7 CMOSN W=100U L=2U AD=500E-12 PD=100U
M3 4 6 7 7 CMOSN W=100U L=2U AD=500E-12 PD=100U
M4 1 10 6 6 CMOSN W=100U L=2U AD=500E-12 PD=100U
IBIAS1 5 2 10UA
IBIAS4 6 2 10UA
IBIAS23 7 2 1MA
RS1 8 9 10K
RS4 10 0 10K
VI 8 0 0V AC
.TF V(3,4) VI
.PLOT AC VDB(3,4)
.PLOT AC VP(3,4)
.AC DEC 10 10K 100MEG
* COX'=0.7FF/UM**2=BOX/TOX => TOX=500 ANGSTROMS
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0 GAMMA=0 VTO=1 KP=60U LD=0.2U
+ CJ=0.4E-15 CJSW=0.4E-15 TOX=500E-10 PB=0.6
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

```

+0:1 = 6.000E+00 0:2 = -6.000E+00 0:3 = 3.500E+00
+0:4 = 3.500E+00 0:5 = -1.073E+00 0:6 = -1.073E+00
+0:7 = -2.589E+00 0:8 = 0. 0:9 = 0.
+0:10 = 0.

```

**** MOSFETS

ELEMENT	0:M1	0:M2	0:M3	0:M4
MODEL	0:CMOSN	0:CMOSN	0:CMOSN	0:CMOSN
ID	1.000E-05	5.000E-04	5.000E-04	1.000E-05
IBS	0.	0.	0.	0.
IBD	-7.073E-14	-6.089E-14	-6.089E-14	-7.073E-14
VGS	1.073E+00	1.516E+00	1.516E+00	1.073E+00
VDS	7.073E+00	6.089E+00	6.089E+00	7.073E+00
VBS	0.	0.	0.	0.
VTH	1.000E+00	1.000E+00	1.000E+00	1.000E+00
VDSAT	7.303E-02	5.164E-01	5.164E-01	7.303E-02
BETA	3.750E-03	3.750E-03	3.750E-03	3.750E-03
GAM EFF	0.	0.	0.	0.
GM	2.739E-04	1.936E-03	1.936E-03	2.739E-04
GDS	0.	0.	0.	0.
GMB	0.	0.	0.	0.
COTOT	1.485E-14	1.471E-14	1.471E-14	1.485E-14
CGTOT	1.253E-13	1.055E-13	1.055E-13	1.253E-13
CSTOT	8.748E-14	8.748E-14	8.748E-14	8.748E-14
CBTOT	2.293E-14	3.346E-15	3.346E-15	2.293E-14
CGS	8.748E-14	8.748E-14	8.748E-14	8.748E-14
CGD	1.485E-14	1.471E-14	1.471E-14	1.485E-14

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(3,4)/VI = -9.682E+00
INPUT RESISTANCE AT VI = 9.999E+19
OUTPUT RESISTANCE AT V(3,4) = 9.999E+03

```

***** AC ANALYSIS

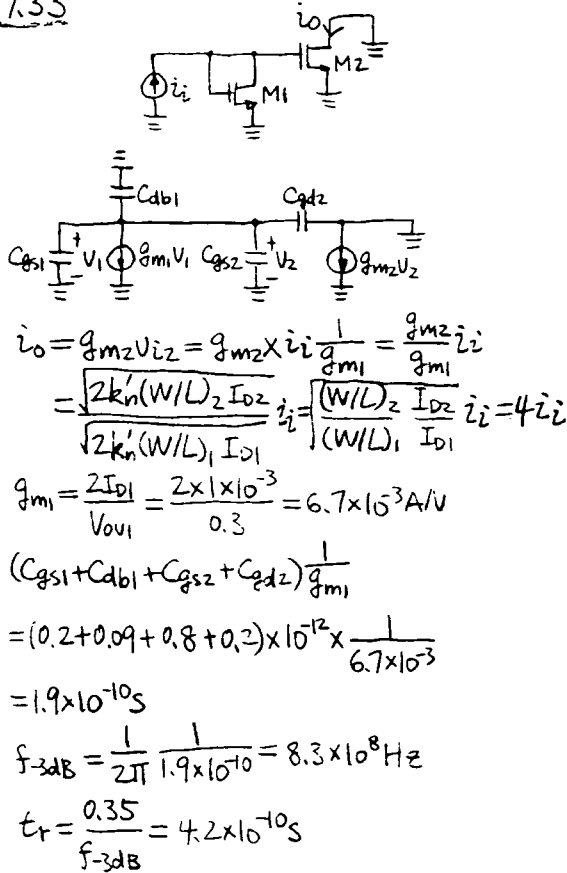
THOM= 27.000 TEMP= 27.000

FREQ	VDB(3,4)	1.940E+01	1.960E+01	1.980E+01	2.000E+01
9.999E+03	1.97E+01	+	+	+	+
1.258E+04	1.97E+01	+	+	+	+
1.584E+04	1.97E+01	+	+	+	+
1.995E+04	1.97E+01	+	+	+	+
2.511E+04	1.97E+01	+	+	+	+
3.162E+04	1.97E+01	+	+	+	+
3.981E+04	1.97E+01	+	+	+	+
5.011E+04	1.97E+01	+	+	+	+
6.309E+04	1.97E+01	+	+	+	+
7.943E+04	1.97E+01	+	+	+	+
1.000E+05	1.97E+01	+	+	+	+
1.258E+05	1.97E+01	+	+	+	+
1.584E+05	1.97E+01	+	+	+	+
1.995E+05	1.97E+01	+	+	+	+
2.511E+05	1.97E+01	+	+	+	+
3.162E+05	1.97E+01	+	+	+	+
3.981E+05	1.97E+01	+	+	+	+
5.011E+05	1.97E+01	+	+	+	+
6.309E+05	1.97E+01	+	+	+	+
7.943E+05	1.97E+01	+	+	+	+
1.000E+06	1.97E+01	+	+	+	+
1.258E+06	1.97E+01	+	+	+	+
1.584E+06	1.97E+01	+	+	+	+
1.995E+06	1.97E+01	+	+	+	+
2.511E+06	1.97E+01	+	+	+	+
3.162E+06	1.97E+01	+	+	+	+
3.981E+06	1.97E+01	+	+	+	+
5.011E+06	1.97E+01	+	+	+	+
6.309E+06	1.97E+01	+	+	+	+
7.943E+06	1.97E+01	+	+	+	+
1.000E+07	1.97E+01	+	+	+	+
1.258E+07	1.97E+01	+	+	+	+
1.584E+07	1.97E+01	+	+	+	+
1.995E+07	1.97E+01	+	+	+	+
2.511E+07	1.97E+01	+	+	+	+
3.162E+07	1.97E+01	+	+	+	+
3.981E+07	1.97E+01	+	+	+	+
5.011E+07	1.98E+01	+	+	+	+
6.309E+07	1.97E+01	+	+	+	+
7.943E+07	1.96E+01	+	+	+	+
1.000E+08	1.93E+01	+	+	+	+

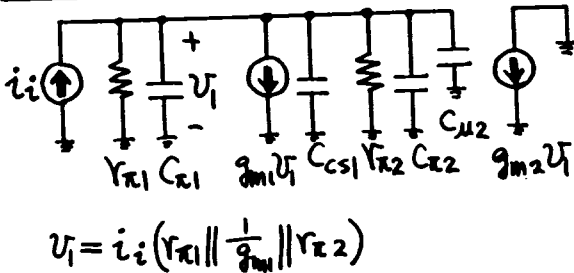
FREQ	VP(3,4)	1.400E+02	1.600E+02	1.800E+02	2.000E+02
9.999E+03	1.80E+02	+	+	+	+
1.258E+04	1.80E+02	+	+	+	+
1.584E+04	1.80E+02	+	+	+	+
1.995E+04	1.80E+02	+	+	+	+
2.511E+04	1.80E+02	+	+	+	+
3.162E+04	1.80E+02	+	+	+	+
3.981E+04	1.80E+02	+	+	+	+
5.011E+04	1.80E+02	+	+	+	+
6.309E+04	1.80E+02	+	+	+	+
7.943E+04	1.80E+02	+	+	+	+
1.000E+05	1.80E+02	+	+	+	+
1.258E+05	1.79E+02	+	+	+	+
1.584E+05	1.79E+02	+	+	+	+
1.995E+05	1.79E+02	+	+	+	+
2.511E+05	1.79E+02	+	+	+	+
3.162E+05	1.79E+02	+	+	+	+
3.981E+05	1.79E+02	+	+	+	+
5.011E+05	1.79E+02	+	+	+	+
6.309E+05	1.79E+02	+	+	+	+
7.943E+05	1.79E+02	+	+	+	+
1.000E+06	1.79E+02	+	+	+	+
1.258E+06	1.79E+02	+	+	+	+
1.584E+06	1.79E+02	+	+	+	+
1.995E+06	1.79E+02	+	+	+	+
2.511E+06	1.79E+02	+	+	+	+
3.162E+06	1.79E+02	+	+	+	+
3.981E+06	1.78E+02	+	+	+	+
5.011E+06	1.78E+02	+	+	+	+
6.309E+06	1.77E+02	+	+	+	+
7.943E+06	1.76E+02	+	+	+	+
1.000E+07	1.75E+02	+	+	+	+
1.258E+07	1.74E+02	+	+	+	+
1.584E+07	1.73E+02	+	+	+	+
1.995E+07	1.72E+02	+	+	+	+
2.511E+07	1.69E+02	+	+	+	+
3.162E+07	1.66E+02	+	+	+	+
3.981E+07	1.63E+02	+	+	+	+
5.011E+07	1.58E+02	+	+	+	+
6.309E+07	1.51E+02	+	+	+	+
7.943E+07	1.43E+02	+	+	+	+
1.000E+08	1.31E+02	+	+	+	+

7-37

7.33



7.34



$$r_{\pi 1} = \frac{\beta}{g_{m1}} = 200 \times 26 = 5.2 \text{ k}\Omega$$

$$\frac{1}{g_{m1}} = 26 \Omega$$

$$r_{\pi 2} = \frac{\beta}{g_{m2}} = 200 \times \frac{26}{4} = 1.3 \text{ k}\Omega$$

$$\therefore V_i = i_i \times 25.37 \Omega$$

$$i_o = g_{m2} V_i = \frac{4}{26} V_i$$

$$\therefore \frac{i_o}{i_i} = \frac{4}{26} \times 25.37 = 3.90$$

$$\text{For } Q_1 \quad C_b = \tau_F g_{m1}$$

$$= 0.2 \times \frac{1}{26} \times 10^{-9} = 7.7 \text{ pF}$$

$$\therefore C_{\pi 1} = 8.7 \text{ pF}$$

$$\text{For } Q_2 \quad C_b = 0.2 \times \frac{4}{26} \times 10^{-9} = 30.8 \text{ pF}$$

$$\therefore C_{\pi 2} = 34.8 \text{ pF}$$

Total shunt C

$$= C_{\pi 1} + C_{cs1} + C_{\pi 2} + C_{\mu 2}$$

$$= 8.7 + 1 + 34.8 + 0.8 = 45.3 \text{ pF}$$

$$r_{\pi 1} \parallel \frac{1}{g_{m1}} \parallel r_{\pi 2} = 25.4 \Omega$$

$$\therefore \text{Time constant} = 45.3 \times 25.4 = 1.15 \text{ ns}$$

$$\therefore f_{-3dB} = 138 \text{ MHz}$$

$$t_r(10-90\%) = \frac{0.35}{f_{-3dB}} = 2.5 \text{ ns}$$

7.35

$$\text{Bias } I_{C6} = \frac{5.4}{6} = 0.9 \text{ mA}$$

$$\therefore I_{C5} \approx \frac{1}{2} \times 0.9 = 0.45 \text{ mA}$$

$$\therefore I_{C1} = I_{C2} = 0.22 \text{ mA}$$

$$\therefore V_{C1} = V_{C2} = 6 - 2.2 = 3.8 \text{ V}$$

$$\therefore I_{C3} = I_{C4} = \frac{1}{2} \times \frac{3.2}{5} = 0.32 \text{ mA}$$

$$\therefore V_{C3} = V_{C4} = 6 - 5 \times 0.32 = 4.4 \text{ V}$$

Parameters

$$Q_1 \quad r_{\pi 1} = \frac{\beta}{g_{m1}} = 200 \times \frac{26}{0.22} = 23.6 \text{ k}\Omega$$

$$C_{\pi} + C_{\mu} = \frac{g_{m1}}{2\pi f_T} = \frac{1}{2\pi \times 26 \times 600 \times 10^6}$$

$$= 10.2 \text{ pF at } I_C = 1 \text{ mA}$$

$$\therefore C_{\pi} = 10 \text{ pF}$$

$$\therefore C_b = 8 \text{ pF at } I_C = 1 \text{ mA}$$

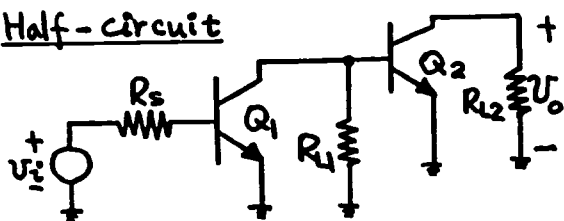
$$= 1.8 \text{ pF at } I_C = 0.22 \text{ mA}$$

$$\therefore C_{\pi 1} = 3.8 \text{ pF}$$

$$Q_2 \quad r_{\pi 2} = 200 \times \frac{26}{0.32} = 16.3 \text{ k}\Omega$$

$$C_b = 2.6 \text{ pF at } 0.32 \text{ mA}$$

$$C_{\pi 2} = 4.6 \text{ pF}$$

Half-circuit

$$\frac{v_o}{v_i} = \frac{r_{\pi 1}}{R_s + r_{\pi 1}} g_{m1} \frac{R_4 r_{\pi 2}}{R_4 + r_{\pi 2}} g_{m2} R_{L2}$$

$$= \frac{23.6}{43.6} \frac{0.22}{26} \frac{10 \times 16.3}{26.3} \times 1000$$

$$= 1747 \quad \times \frac{0.32}{26} \times 5000$$

$$\therefore \text{Circuit gain} = \frac{1}{2} \times 1747 = 873$$

$$R_{\pi 01} = R_s \parallel r_{\pi 1} = 20 \text{ k} \parallel 23.6 \text{ k} = 10.8 \text{ k}\Omega$$

$$C_{\pi 1} R_{\pi 01} = 3.8 \times 10.8 = 41.1 \text{ ns}$$

$$R_{\mu 01} = R_{\pi 01} + R_1 + g_{m1} R_{\pi 01} R_1$$

$$R_1 = R_4 \parallel r_{\pi 2} = 10 \parallel 16.3 = 6.2 \text{ k}\Omega$$

$$\therefore R_{\mu 01} = 10.8 + 6.2 + \frac{0.22}{26} \times 6200 \times 10.8$$

$$= 584 \text{ k}\Omega$$

$$\therefore C_{\mu 1} R_{\mu 01} = 0.2 \times 584 = 117 \text{ ns}$$

$$C_{c1} R_1 = 1 \times 6.2 = 6.2 \text{ ns}$$

$$R_{\pi 02} = R_1 = 6.2 \text{ k}\Omega$$

$$\therefore C_{\pi 2} R_{\pi 02} = 4.6 \times 6.2 = 28.5 \text{ ns}$$

$$R_{\mu 02} = R_{\pi 02} + R_{L2} + g_{m2} R_{L2} R_{\pi 02}$$

$$= 6.2 + 5 + \frac{0.32}{26} \times 5000 \times 6.2$$

$$= 393 \text{ k}\Omega$$

$$\therefore C_{\mu 2} R_{\mu 02} = 0.2 \times 393 = 79 \text{ ns}$$

$$C_{c2} R_{L2} = 1 \times 5 = 5 \text{ ns}$$

$$\therefore \Sigma T_0 = 41.1 + 117 + 6.2 + 28.5 + 79 + 5$$

$$= 276 \text{ ns}$$

$$\therefore f_{-3dB} = \frac{1}{2\pi \Sigma T_0} = 576 \text{ kHz}$$

$$t_r(10-90\%) = \frac{0.35}{f_{-3dB}} = 608 \text{ ns}$$

7-39

TWO-STAGE AMPLIFIER

```

VCC 1 0 6V
VEE 2 0 -6V
RL1 1 3 10K
RL2 1 4 10K
Q1 3 5 7 NPN
Q2 4 6 7 NPN
RS1 8 5 20K
RS2 6 0 20K
RL3 1 13 5K
RL4 1 14 5K
Q3 13 3 12 NPN
Q4 14 4 12 NPN
RKE34 12 0 5K
Q5 7 11 9 NPN
Q6 11 11 10 NPN
RE5 9 2 2K
RE6 10 2 1K
RBIAS 11 0 5K
VI 8 0 0V AC
.PLOT AC VDB(14)
.PLOT AC VP(14)
.AC DEC 10 10K 100MEG
.MODEL NPN NPN IS=1E-16A BF=200 RB=0
+ CJE=2PF CJC=0.3PF CJS=3PF TF=213PS
+ MJE=0.5 MJC=0.5 MJS=0.5 VJE=0.55 VJC=0.55 VJS=0.55
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

```

+0:1 = 6.000E+00 0:2 = -6.000E+00 0:3 = 3.789E+00
+0:4 = 3.789E+00 0:5 = -2.196E-02 0:6 = -2.196E-02
+0:7 = -7.570E-01 0:8 = 0. 0:9 = -5.112E+00
+0:10 = -5.130E+00 0:11 = -4.359E+00 0:12 = 3.045E+00
+0:13 = 4.484E+00 0:14 = 4.484E+00

```

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	0:Q1	0:Q2	0:Q3	0:Q4	0:Q5	0:Q6
MODEL	0:NPN	0:NPN	0:NPN	0:NPN	0:NPN	0:NPN
IB	1.098E-06	1.098E-06	1.515E-06	1.515E-06	2.207E-06	4.327E-06
IC	2.196E-04	2.196E-04	3.030E-04	3.030E-04	4.414E-04	8.654E-04
VBE	7.350E-01	7.350E-01	7.433E-01	7.433E-01	7.531E-01	7.705E-01
VCE	4.545E+00	4.545E+00	1.439E+00	1.439E+00	4.355E+00	7.705E-01
VBC	-3.810E+00	-3.810E+00	-6.958E-01	-6.958E-01	-3.602E+00	0.
VS	-3.789E+00	-3.789E+00	-4.484E+00	-4.484E+00	7.570E-01	4.359E+00
POWER	9.990E-04	9.990E-04	4.373E-04	4.373E-04	1.924E-03	6.701E-04
BETAD	2.000E+02	2.000E+02	2.000E+02	2.000E+02	2.000E+02	2.000E+02
GM	8.490E-03	8.490E-03	1.172E-02	1.172E-02	1.707E-02	3.346E-02
RPI	2.355E+04	2.355E+04	1.706E+04	1.706E+04	1.172E+04	5.977E+03
RX	0.	0.	0.	0.	0.	0.
RO	3.810E+16	3.810E+16	6.958E+15	6.958E+15	3.602E+16	2.586E+14
CPI	7.002E-12	7.002E-12	7.733E-12	7.733E-12	8.922E-12	1.250E-11
CMU	1.065E-13	1.065E-13	1.993E-13	1.993E-13	1.092E-13	3.000E-13
CBX	0.	0.	0.	0.	0.	0.
CCS	1.068E-12	1.068E-12	9.915E-13	9.915E-13	5.064E-12	1.489E-11
BETAAC	2.000E+02	2.000E+02	2.000E+02	2.000E+02	2.000E+02	2.000E+02
FT	1.900E+08	1.900E+08	2.351E+08	2.351E+08	3.007E+08	4.159E+08

***** AC ANALYSIS

THOM= 27.000 TEMP= 27.000

FREQ	VDB(14)	0.	2.000E+01	4.000E+01	6.000E+01
9.999E+03	5.85E+01	+	+	+	+
1.258E+04	5.85E+01	+	+	+	+
1.584E+04	5.85E+01	+	+	+	+
1.995E+04	5.85E+01	+	+	+	+
2.511E+04	5.85E+01	+	+	+	+
3.162E+04	5.85E+01	+	+	+	+
3.981E+04	5.85E+01	+	+	+	+
5.011E+04	5.85E+01	+	+	+	+
6.309E+04	5.85E+01	+	+	+	+
7.943E+04	5.85E+01	+	+	+	+
1.000E+05	5.84E+01	+	+	+	+
1.258E+05	5.84E+01	+	+	+	+
1.584E+05	5.83E+01	+	+	+	+
1.995E+05	5.82E+01	+	+	+	+
2.511E+05	5.80E+01	+	+	+	+
3.162E+05	5.77E+01	+	+	+	+
3.981E+05	5.73E+01	+	+	+	+
5.011E+05	5.66E+01	+	+	+	+
6.309E+05	5.58E+01	+	+	+	+
7.943E+05	5.47E+01	+	+	+	+
1.000E+06	5.34E+01	+	+	+	+
1.258E+06	5.17E+01	+	+	+	+
1.584E+06	4.98E+01	+	+	+	+
1.995E+06	4.77E+01	+	+	+	+
2.511E+06	4.52E+01	+	+	+	+
3.162E+06	4.26E+01	+	+	+	+
3.981E+06	3.96E+01	+	+	+	+
5.011E+06	3.64E+01	+	+	+	+
6.309E+06	3.30E+01	+	+	+	+
7.943E+06	2.94E+01	+	+	+	+
1.000E+07	2.57E+01	+	+	+	+
1.258E+07	2.18E+01	+	+	+	+
1.584E+07	1.78E+01	+	+	+	+
1.995E+07	1.35E+01	+	+	+	+
2.511E+07	8.88E+00	+	+	+	+
3.162E+07	4.35E+00	+	+	+	+
3.981E+07	-9.98E-02	+	+	+	+
5.011E+07	-4.65E-00	+	+	+	+
6.309E+07	-9.41E-00	+	+	+	+
7.943E+07	-1.44E+01	+	+	+	+
1.000E+08	-1.96E+01	+	+	+	+

FREQ	VP(14)	0.	1.000E+02	2.000E+02	3.000E+02
9.999E+03	1.79E+02	+	+	+	+
1.258E+04	1.78E+02	+	+	+	+
1.584E+04	1.78E+02	+	+	+	+
1.995E+04	1.78E+02	+	+	+	+
2.511E+04	1.77E+02	+	+	+	+
3.162E+04	1.76E+02	+	+	+	+
3.981E+04	1.76E+02	+	+	+	+
5.011E+04	1.75E+02	+	+	+	+
6.309E+04	1.73E+02	+	+	+	+
7.943E+04	1.72E+02	+	+	+	+
1.000E+05	1.70E+02	+	+	+	+
1.258E+05	1.67E+02	+	+	+	+
1.584E+05	1.64E+02	+	+	+	+
1.995E+05	1.60E+02	+	+	+	+
2.511E+05	1.55E+02	+	+	+	+
3.162E+05	1.50E+02	+	+	+	+
3.981E+05	1.43E+02	+	+	+	+
5.011E+05	1.35E+02	+	+	+	+
6.309E+05	1.27E+02	+	+	+	+
7.943E+05	1.17E+02	+	+	+	+
1.000E+06	1.07E+02	+	+	+	+
1.258E+06	9.77E+01	+	+	+	+
1.584E+06	8.75E+01	+	+	+	+
1.995E+06	7.72E+01	+	+	+	+
2.511E+06	6.70E+01	+	+	+	+
3.162E+06	5.68E+01	+	+	+	+
3.981E+06	4.70E+01	+	+	+	+
5.011E+06	3.77E+01	+	+	+	+
6.309E+06	2.90E+01	+	+	+	+
7.943E+06	2.10E+01	+	+	+	+
1.000E+07	1.35E+01	+	+	+	+
1.258E+07	5.98E+00	+	+	+	+
1.584E+07	-2.16E+00	+	+	+	+
1.995E+07	-1.02E+01	+	+	+	+
2.511E+07	-1.61E+01	+	+	+	+
3.162E+07	-2.06E+01	+	+	+	+
3.981E+07	-2.56E+01	+	+	+	+
5.011E+07	-3.15E+01	+	+	+	+
6.309E+07	-3.79E+01	+	+	+	+
7.943E+07	-4.44E+01	+	+	+	+
1.000E+08	-5.05E+01	+	+	+	+

7-40

7.36

Bias $I_{C3} = \frac{5.4}{11} = 0.49 \text{ mA}$

$\therefore I_{C4} \approx \frac{0.49}{2.5} = 196 \mu\text{A}$

$\therefore I_{C1} = I_{C2} = 98 \mu\text{A}$

$\therefore V_{C2} \approx 6 - 0.098 \times 12.5 = 4.77 \text{ V}$

$\therefore I_{C3} = \frac{1.227 - 0.6}{1} = 0.627 \text{ mA}$

$I_{B3} = 6 \mu\text{A}$

Recalculate

$V_{C2} = 6 - 0.092 \times 12.5 = 4.85 \text{ V}$

$\therefore I_{C3} = \frac{1.15 - 0.6}{1} = 0.55 \text{ mA}$

Parameters

Q1 $r_{\pi 1} = \frac{\beta}{g_{m1}} = 200 \times \frac{26}{0.098} = 53.1 \text{ k}\Omega$

$C_{\pi} + C_{\mu} = \frac{g_{m1}}{2\pi f_T} = \frac{1}{2\pi \times 26 \times 400 \times 10^6}$

$= 15.3 \text{ pF at } 1 \text{ mA}$

$\therefore C_{\pi} = 15 \text{ pF at } 1 \text{ mA}$

$C_b = 12 \text{ pF at } 1 \text{ mA}$

$= 1.2 \text{ pF at } 0.098 \text{ mA}$

$\therefore C_{\pi 1} = 4.2 \text{ pF}$

Q3 $r_{\pi 3} = \frac{\beta}{g_{m3}} = 100 \times \frac{26}{0.55} = 4.7 \text{ k}\Omega$

$C_{b3} + C_{\pi} + C_{\mu} = \frac{g_{m3}}{2\pi f_T}$

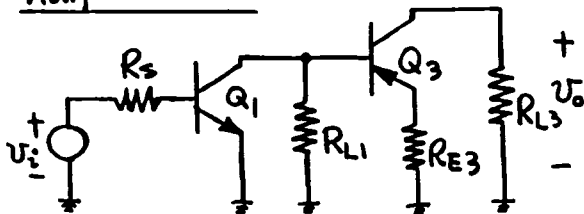
$= \frac{0.5}{2\pi \times 26 \times 6 \times 10^6} = 510 \text{ pF}$

$\therefore C_b = 505 \text{ pF at } 0.5 \text{ mA}$

$= 555 \text{ pF at } 0.55 \text{ mA}$

$\therefore C_{\pi 3} = 558 \text{ pF}$

Half-circuit



$\frac{v_o}{v_i} = \frac{r_{\pi 1}}{r_{\pi 1} + R_s} g_{m1} \frac{R_L1 R_{i3}}{R_L1 + R_{i3}} G_{m3} R_{L3}$

$R_{i3} = r_{\pi 3} (1 + g_{m3} R_{E3})$

$= 4.7 (1 + \frac{0.55}{26} \times 1000) = 104 \text{ k}\Omega$

$G_{m3} = \frac{g_{m3}}{1 + g_{m3} R_{E3}} = \frac{0.55}{26 \cdot 22.2}$

$= 0.953 \text{ mA/V}$

$\therefore \frac{v_o}{v_i} = \frac{53.1}{63.1} \times \frac{0.098}{26} \times \frac{12.5 \times 104}{116.5} \times 1000 \times 0.953 \times 10$

$= 337$

Actual gain $= \frac{1}{2} \times 337 = 169$

$R_{\pi 01} = R_s \parallel r_{\pi 1} = 10 \parallel 53.1 = 8.42 \text{ k}\Omega$

$\therefore C_{\pi 1} R_{\pi 01} = 4.2 \times 8.42 = 35.4 \text{ ns}$

$R_{\mu 01} = R_{\pi 01} + R_1 + g_{m1} R_{\pi 01} R_1$

$R_1 = R_L1 \parallel R_{i3} = 12.5 \parallel 104 = 11.2 \text{ k}\Omega$

$\therefore R_{\mu 01} = 8.42 + 11.2 + \frac{0.098}{26} \times 8420 \times 11.2 = 375 \text{ k}\Omega$

$\therefore C_{\mu 1} R_{\mu 01} = 0.3 \times 375 = 112 \text{ ns}$

$C_{cs1} R_1 = 1.5 \times 11.2 = 16.8 \text{ ns}$

$C_{bs3} R_1 = 1.5 \times 11.2 = 16.8 \text{ ns}$

$R_{\pi 03} = r_{\pi 3} \parallel \frac{R_L1 + R_{E3}}{1 + g_{m3} R_{E3}} = 4.7 \parallel \frac{12.6 \text{ k}}{22.2}$

$= 4.7 \text{ k} \parallel 608 = 538 \Omega$

$\therefore C_{\pi 3} R_{\pi 03} = 558 \times 0.538 = 300 \text{ ns}$

$R_{\mu 03} = R_1 + R_{L3} + G_m R_1 R_{L3}$

$R_1 = R_L1 \parallel R_{i3} = 11.2 \text{ k}\Omega$

$\therefore R_{\mu 03} = 11.2 + 10 + 0.953 \times 10 \times 11.2 = 128 \text{ k}\Omega$

$\therefore C_{\mu 3} R_{\mu 03} = 0.3 \times 128 = 38.4 \text{ ns}$

$\therefore \Sigma T_0 = 35.4 + 112 + 16.8 \times 2 + 300 + 38.4 = 519 \text{ ns}$

$\therefore f_{-3dB} = \frac{1}{2\pi \Sigma T_0} = 306 \text{ kHz}$

7-41

TWO-STAGE AMPLIFIER

```

VCC 1 0 5V
VEE 2 0 -6V
RL1 1 3 12.5K
RL2 1 4 12.5K
Q1 3 5 7 NPN
Q2 4 6 7 NPN
RS1 8 5 10K
RS2 6 0 10K
Q4 7 9 10 NPN
RQ4 10 2 2.5K
Q5 9 9 11 NPN
RQ5 11 2 1K
RBIAS 9 0 10K
Q3 12 4 13 PNP
RQ3 1 13 1K
RL3 12 2 10K
VI 8 0 0V AC
.PLOT AC VDB(12)
.PLOT AC VP(12)
.AC DEC 10 10K 100MEG
.MODEL NPN NPN IS=9.31E-15A BF=200 RB=0
+ CJE=3PF CJC=0.58PF CJS=1.5PF TF=318PS
.MODEL PNP PNP IS=52.3E-15A BF=100 RB=0
+ CJE=3PF CJC=0.58PF CJS=1.5PF TF=26.2PS
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

```

+0:1 = 6.000E+00 0:2 = -6.000E+00 0:3 = 4.740E+00
+0:4 = 4.812E+00 0:5 = -5.040E-03 0:6 = -5.040E-03
+0:7 = -6.026E-01 0:8 = 0. 0:9 = -4.875E+00
+0:10 = -5.491E+00 0:11 = -5.513E+00 0:12 = -1.707E-01
+0:13 = 5.411E+00

```

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	Q:Q1	Q:Q2	Q:Q4	Q:Q5	Q:Q3
MODEL	0:MPN	0:MPN	0:MPN	0:MPN	0:PNP
IB	5.040E-07	5.040E-07	1.013E-06	2.420E-06	-5.829E-06
IC	1.008E-04	1.008E-04	2.026E-04	4.841E-04	-5.829E-04
VBE	5.976E-01	5.976E-01	6.157E-01	6.382E-01	-5.984E-01
VCE	5.342E+00	5.415E+00	4.888E+00	6.382E-01	-5.581E+00
VBC	-4.745E+00	-4.817E+00	-4.272E+00	0.	4.983E+00
VS	-4.740E+00	-4.812E+00	6.026E-01	4.875E+00	-4.812E+00
POWER	5.388E-04	5.462E-04	9.910E-04	3.105E-04	3.257E-03
BETAD	2.000E+02	2.000E+02	2.000E+02	2.000E+02	1.000E+02
GM	3.897E-03	3.897E-03	7.833E-03	1.872E-02	2.254E-02
RPI	5.131E+04	5.131E+04	2.553E+04	1.068E+04	4.436E+03
RI	0.	0.	0.	0.	0.
RO	5.096E+14	5.175E+14	4.589E+14	2.778E+12	9.528E+13
CPI	5.749E-12	5.749E-12	7.061E-12	1.060E-11	5.103E-12
CMO	3.006E-13	2.993E-13	3.097E-13	5.800E-13	2.964E-13
CRX	0.	0.	0.	0.	0.
CCS	1.500E-12	1.500E-12	1.500E-12	1.500E-12	1.500E-12
BETAAC	2.000E+02	2.000E+02	2.000E+02	2.000E+02	9.999E+01
FT	1.025E+08	1.025E+08	1.691E+08	2.665E+08	6.643E+08

***** AC ANALYSIS

THOM= 27.000 TEMP= 27.000

FREQ	VDB(12)	VP(12)
(A)	-1.000E+02	0.
9.999E+03	4.47E+01	-A-
1.258E+04	4.47E+01	A+
1.584E+04	4.47E+01	A+
1.995E+04	4.47E+01	A+
2.511E+04	4.47E+01	A+
3.162E+04	4.47E+01	A+
3.981E+04	4.47E+01	A+
5.011E+04	4.47E+01	A+
6.309E+04	4.47E+01	A+
7.943E+04	4.47E+01	A+
1.000E+05	4.46E+01	-A-
1.258E+05	4.46E+01	A+
1.584E+05	4.45E+01	A+
1.995E+05	4.44E+01	A+
2.511E+05	4.43E+01	A+
3.162E+05	4.40E+01	A+
3.981E+05	4.36E+01	A+
5.011E+05	4.31E+01	A+
6.309E+05	4.24E+01	A+
7.943E+05	4.14E+01	A+
1.000E+06	4.01E+01	-A-
1.258E+06	3.86E+01	A+
1.584E+06	3.68E+01	A+
1.995E+06	3.47E+01	A+
2.511E+06	3.24E+01	A+
3.162E+06	2.99E+01	A+
3.981E+06	2.73E+01	A+
5.011E+06	2.45E+01	A+
6.309E+06	2.16E+01	A+
7.943E+06	1.88E+01	A+
1.000E+07	1.60E+01	-A-
1.258E+07	1.31E+01	A+
1.584E+07	1.02E+01	A+
1.995E+07	7.04E+00	A+
2.511E+07	3.43E+00	A+
3.162E+07	-9.39E-01	A+
3.981E+07	-6.30E+00	A+
5.011E+07	-1.24E+01	A+
6.309E+07	-1.87E+01	A+
7.943E+07	-2.44E+01	A+
1.000E+08	-2.94E+01	A+
FREQ <th>VP(12)</th>	VP(12)	
(A)	-1.000E+02	
9.999E+03	1.79E+02	
1.258E+04	1.78E+02	
1.584E+04	1.78E+02	
1.995E+04	1.78E+02	
2.511E+04	1.77E+02	
3.162E+04	1.77E+02	
3.981E+04	1.76E+02	
5.011E+04	1.75E+02	
6.309E+04	1.74E+02	
7.943E+04	1.73E+02	
1.000E+05	1.71E+02	
1.258E+05	1.69E+02	
1.584E+05	1.66E+02	
1.995E+05	1.62E+02	
2.511E+05	1.58E+02	
3.162E+05	1.53E+02	
3.981E+05	1.47E+02	
5.011E+05	1.40E+02	
6.309E+05	1.32E+02	
7.943E+05	1.23E+02	
1.000E+06	1.14E+02	
1.258E+06	1.05E+02	
1.584E+06	9.57E+01	
1.995E+06	8.67E+01	
2.511E+06	7.61E+01	
3.162E+06	7.02E+01	
3.981E+06	6.30E+01	
5.011E+06	5.65E+01	
6.309E+06	5.05E+01	
7.943E+06	4.45E+01	
1.000E+07	3.80E+01	
1.258E+07	3.04E+01	
1.584E+07	2.08E+01	
1.995E+07	9.31E+00	
2.511E+07	-5.51E+00	
3.162E+07	-2.18E+01	
3.981E+07	-3.71E+01	
5.011E+07	-4.73E+01	
6.309E+07	-5.07E+01	
7.943E+07	-4.89E+01	
1.000E+08	-4.53E+01	

7-37 (a)

$$V_0 = 2.5 \text{ V dc}$$

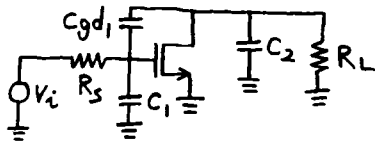
$$V_{GS2} = 2.5 \text{ V}$$

$$\begin{aligned} V_{t2} &= V_{t0} + \gamma(\sqrt{2\phi_f + V_{SB}} - \sqrt{2\phi_f}) \\ &= 0.7 + 0.4(\sqrt{0.6 + 2.5} - \sqrt{0.6}) \\ &= 1.09 \text{ V} \end{aligned}$$

$$\begin{aligned} I_D &= \frac{\mu_n C_{ox}}{2} \left(\frac{W}{L}\right)_2 (V_{GS2} - V_{t2})^2 \\ &= \frac{60\mu}{2} \frac{4}{1} (2.5 - 1.09)^2 \\ &= 237 \mu\text{A} \end{aligned}$$

$$\begin{aligned} \frac{V_o}{V_i} &= \frac{-g_{m1}}{g_{m2} + g_{mb2}} = \frac{-1.69\text{m}}{337\mu + 38.3\mu} \\ &= -4.5 \end{aligned}$$

$$\begin{aligned} g_{m1} &= \sqrt{2I_D \mu C_{ox} \frac{W}{L}} \\ &= \sqrt{2(237\mu)(60\mu)(100)} \\ &= 1.69 \text{ mA/V} \\ g_{m2} &= \sqrt{2(237\mu)(60\mu)(4)} \\ &= 337 \mu\text{A/V} \\ g_{mb2} &= \frac{g_{m2} \gamma}{2\sqrt{2\phi_f + V_{SB}}} = \frac{g_{m2} 0.4}{2\sqrt{0.6 + 2.5}} \\ &= 38.3 \mu\text{A/V} \end{aligned}$$



$$C_{ox} = 1.73 \frac{\text{fF}}{\mu^2}$$

7-42

$$\begin{aligned} C_{gs1} &= \frac{2}{3} W L C_{ox} + C_{ol} W \\ &= 115 \text{ fF} + 30 \text{ fF} = 145 \text{ fF} \end{aligned}$$

$$\begin{aligned} C_{gs2} &= \frac{2}{3} W L C_{ox} + C_{ol} W \\ &= 4.61 \text{ fF} + 1.2 \text{ fF} \\ &= 5.8 \text{ fF} \end{aligned}$$

$$C_{db1} = \frac{0.8(100)}{\sqrt{1 + \frac{2.5}{0.6}}} = 35.2 \text{ fF}$$

$$C_{gd1} = C_{ol} W = 30 \text{ fF}$$

$$C_{sb2} = \frac{0.8(4)}{\sqrt{1 + \frac{2.5}{0.6}}} = 1.41 \text{ fF}$$

$$C_1 = C_{gs1} = 145 \text{ fF}$$

$$\begin{aligned} C_2 &= C_{db1} + C_{sb2} + C_{gs2} + C_L \\ &= 142 \text{ fF} \end{aligned}$$

$$C_1 R_S = 145 \text{ ps}$$

$$\begin{aligned} C_2 R_L &= 142 \text{ fF} (2665 \Omega) \\ &= 378 \text{ ps} \end{aligned}$$

$$\begin{aligned} C_{gd1}(R_S + R_L + g_m R_S R_L) \\ &= 30(1\text{k} + 2665 + 1.69\text{m}(1\text{k})(2665)) \text{ f} \\ &= 245 \text{ ps} \end{aligned}$$

$$\begin{aligned} f_{-3\text{dB}} &= \frac{1}{2\pi} \frac{10^{12}}{145 + 378 + 245} \\ &= 207 \text{ MHz} \end{aligned}$$

(b)

$$R_{SX} = \frac{1}{E_c \mu C_{ox} W}$$

$$\begin{aligned} m1 R_{SX} &= \frac{1}{1.5\text{M} \cdot 60\mu \cdot 100\mu} \\ &= 111 \Omega \end{aligned}$$

7-43

$$m_2 R_{sx} = \frac{1}{1.5M \ 60\mu \ 4\mu}$$

$$= 2.78 \text{ k}$$

$$R_L' = R_{sx2} + \frac{1}{g_{m2} + g_{mb2}}$$

$$= 2.78 \text{ k} + 2.66 \text{ k}$$

$$= 5.44 \text{ k}$$

$$g_{m1}' = \frac{g_{m1}}{1 + g_{m1} R_{sx1}}$$

$$= 1.42 \text{ mA/V}$$

$$\frac{V_o}{V_i} = -g_{m1}' R_L' = -7.74$$

$$C_1 R_s = 145 \text{ ps unchanged}$$

$$C_2 R_L' = C_2 R_L \frac{R_L'}{R_L}$$

$$= 378 \text{ ps} (2.04)$$

$$= 772 \text{ ps}$$

$$C_{gd1} (R_s + R_L' + g_{m1}' R_L' R_s)$$

$$= 30 \text{ f} (1 \text{ k} + 5.44 \text{ k} + 1.42 \text{ m} (5.44 \text{ k}) (1 \text{ k}))$$

$$= 425 \text{ ps}$$

$$f_{-3\text{dB}} = \frac{1}{2\pi} \frac{10^{12}}{145 + 772 + 425}$$

$$= 119 \text{ MHz}$$

7-44

```

NMOS AMP
VDD 1 0 5V
M2 1 1 2 0 NMOS2 W=4U L=1U
M1 2 3 0 0 NMOS W=100U L=1U
CLOAD 2 0 100PF
RS 4 3 1K

```

```

VI 4 0 0.981V AC

```

```

.PLOT AC VDB(2)

```

```

.PLOT AC VP(2)

```

```

.AC DEC 15 1MEG 2GIG

```

```

.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4

```

```

+ TOX=20NM CGSO=300PF CGDO=300PF CBD=80PF CBS=80PF

```

```

.MODEL NMOS2 NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4

```

```

+ TOX=20NM CGSO=300PF CGDO=300PF CBD=3.2PF CBS=3.2PF

```

```

.OPTIONS NOPAGE NOMOD

```

```

.WIDTH OUT=80

```

```

.OPTIONS SPICE

```

```

.OP

```

```

.END

```

```

***** OPERATING POINT INFORMATION TNOH= 27.000 TEMP= 27.000

```

```

+0:1 = 5.000E+00 0:2 = 2.500E+00 0:3 = 9.810E-01

```

```

+0:4 = 9.810E-01

```

```

**** MOSFETS

```

```

ELEMENT 0:M2 0:M1

```

```

MODEL 0:NMOS2 0:NMOS

```

```

ID 2.369E-04 2.369E-04

```

```

IBS -2.501E-14 0.

```

```

IBD -5.000E-14 -2.501E-14

```

```

VGS 2.499E+00 9.810E-01

```

```

VDS 2.499E+00 2.500E+00

```

```

VBS -2.500E+00 0.

```

```

VTH 1.094E+00 7.000E-01

```

```

VDSAT 1.405E+00 2.810E-01

```

```

BETA 2.400E-04 6.000E-03

```

```

GAM KFF 4.000E-01 4.000E-01

```

```

GM 3.372E-04 1.686E-03

```

```

GMB 3.830E-05 4.353E-04

```

```

CITOT 2.411E-15 6.996E-14

```

```

CGTOT 7.037E-15 1.780E-13

```

```

CSTOT 7.380E-15 2.251E-13

```

```

CBTOT 2.774E-15 1.217E-13

```

```

CGS 5.804E-15 1.451E-13

```

```

CGD 1.223E-15 3.058E-14

```

```

***** AC ANALYSIS

```

```

TNOH= 27.000 TEMP= 27.000

```

```

FREQ VDB(2)
(A) -2.000E+01 -1.000E+01 0. 1.000E+01 2.000E+01

```

```

1.000E+06 1.30E+01 + + + + + A + +

```

```

1.165E+06 1.30E+01 + + + + + A + +

```

```

1.359E+06 1.30E+01 + + + + + A + +

```

```

1.584E+06 1.30E+01 + + + + + A + +

```

```

1.847E+06 1.30E+01 + + + + + A + +

```

```

2.154E+06 1.30E+01 + + + + + A + +

```

```

2.511E+06 1.30E+01 + + + + + A + +

```

```

2.928E+06 1.30E+01 + + + + + A + +

```

```

3.414E+06 1.30E+01 + + + + + A + +

```

```

3.981E+06 1.30E+01 + + + + + A + +

```

```

4.641E+06 1.30E+01 + + + + + A + +

```

```

5.411E+06 1.30E+01 + + + + + A + +

```

```

6.309E+06 1.30E+01 + + + + + A + +

```

```

7.356E+06 1.30E+01 + + + + + A + +

```

```

8.577E+06 1.30E+01 + + + + + A + +

```

```

1.000E+07 1.30E+01 + + + + + A + +

```

```

1.165E+07 1.30E+01 + + + + + A + +

```

```

1.359E+07 1.30E+01 + + + + + A + +

```

```

1.584E+07 1.30E+01 + + + + + A + +

```

```

1.847E+07 1.30E+01 + + + + + A + +

```

```

2.154E+07 1.30E+01 + + + + + A + +

```

```

2.511E+07 1.30E+01 + + + + + A + +

```

```

2.928E+07 1.29E+01 + + + + + A + +

```

```

3.414E+07 1.29E+01 + + + + + A + +

```

```

3.981E+07 1.29E+01 + + + + + A + +

```

```

4.641E+07 1.29E+01 + + + + + A + +

```

```

5.411E+07 1.28E+01 + + + + + A + +

```

```

6.309E+07 1.27E+01 + + + + + A + +

```

```

7.356E+07 1.26E+01 + + + + + A + +

```

```

8.577E+07 1.25E+01 + + + + + A + +

```

```

1.000E+08 1.23E+01 + + + + + A + +

```

```

1.165E+08 1.20E+01 + + + + + A + +

```

```

1.359E+08 1.17E+01 + + + + + A + +

```

```

1.584E+08 1.14E+01 + + + + + A + +

```

```

1.847E+08 1.09E+01 + + + + + A + +

```

```

2.154E+08 1.03E+01 + + + + + A + +

```

```

2.511E+08 9.66E+00 + + + + + A + +

```

```

2.928E+08 8.96E+00 + + + + + A + +

```

```

3.414E+08 7.93E+00 + + + + + A + +

```

```

3.981E+08 6.90E+00 + + + + + A + +

```

```

4.641E+08 5.75E+00 + + + + + A + +

```

```

5.411E+08 4.50E+00 + + + + + A + +

```

```

6.309E+08 3.14E+00 + + + + + A + +

```

```

7.356E+08 1.67E+00 + + + + + A + +

```

```

8.577E+08 9.97E+00 + + + + + A + +

```

```

1.000E+09 1.58E+00 + + + + + A + +

```

```

1.165E+09 3.38E+00 + + + + + A + +

```

```

1.359E+09 5.08E+00 + + + + + A + +

```

```

1.584E+09 7.90E+00 + + + + + A + +

```

```

1.847E+09 9.40E+00 + + + + + A + +

```

```

2.154E+09 1.15E+01 + + + + + A + +

```

FREQ	VP(2)	5.000E+01	1.000E+02	1.500E+02	2.000E+02
1.000E+06	1.79E+02				A
1.165E+06	1.79E+02				A
1.359E+06	1.79E+02				A
1.584E+06	1.79E+02				A
1.847E+06	1.79E+02				A
2.154E+06	1.79E+02				A
2.511E+06	1.79E+02				A
2.928E+06	1.79E+02				A
3.414E+06	1.79E+02				A
3.981E+06	1.79E+02				A
4.641E+06	1.79E+02				A
5.411E+06	1.78E+02				A
6.309E+06	1.78E+02				A
7.356E+06	1.77E+02				A
8.577E+06	1.77E+02				A
1.000E+07	1.77E+02				A
1.165E+07	1.76E+02				A
1.359E+07	1.76E+02				A
1.584E+07	1.75E+02				A
1.847E+07	1.74E+02				A
2.154E+07	1.73E+02				A
2.511E+07	1.72E+02				A
2.928E+07	1.71E+02				A
3.414E+07	1.70E+02				A
3.981E+07	1.68E+02				A
4.641E+07	1.66E+02				A
5.411E+07	1.64E+02				A
6.309E+07	1.62E+02				A
7.356E+07	1.59E+02				A
8.577E+07	1.55E+02				A
1.000E+08	1.52E+02				A
1.165E+08	1.48E+02				A
1.359E+08	1.43E+02				A
1.584E+08	1.38E+02				A
1.847E+08	1.33E+02				A
2.154E+08	1.27E+02				A
2.511E+08	1.21E+02				A
2.928E+08	1.14E+02				A
3.414E+08	1.08E+02				A
3.981E+08	1.01E+02				A
4.641E+08	9.45E+01				A
5.411E+08	8.76E+01				A
6.309E+08	8.07E+01				A
7.356E+08	7.36E+01				A
8.577E+08	6.65E+01				A
1.000E+09	5.93E+01				A
1.165E+09	5.20E+01				A
1.359E+09	4.48E+01				A
1.584E+09	3.76E+01				A
1.847E+09	3.05E+01				A
2.154E+09	2.35E+01				A

7-45

```

NMOS AMP, EXAMINE SMALL SIGNAL BANDWIDTH AS DC VIN VARIES
VDD 1 0 5V
M2 1 1 2 0 NMOS2 W=4U L=1U
M1 2 3 0 0 NMOS W=100U L=1U
CLOAD 2 0 100PF
RS 4 3 1K
VI 4 0 0.5V AC
.PLOT AC VDB(2)
.PLOT AC VP(2)
.AC DEC 15 1MEG 2GIG
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=80PF CBS=80PF
.MODEL NMOS2 NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=3.2PF CBS=3.2PF
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** AC ANALYSIS

TNOM= 27.000 TEMP= 27.000

FREQ	VDB(2)				
(A)		-2.000E+01	-1.800E+01	-1.600E+01	-1.400E+01
3.981E+07	-1.50E+01	+	+	+	+
4.641E+07	-1.50E+01	+	+	+	+
5.411E+07	-1.50E+01	+	+	+	+
6.309E+07	-1.50E+01	+	+	+	+
7.356E+07	-1.50E+01	+	+	+	+
8.577E+07	-1.50E+01	+	+	+	+
1.000E+08	-1.51E+01	+	+	+	+
1.165E+08	-1.51E+01	+	+	+	+
1.359E+08	-1.51E+01	+	+	+	+
1.584E+08	-1.51E+01	+	+	+	+
1.847E+08	-1.51E+01	+	+	+	+
2.154E+08	-1.51E+01	+	+	+	+
2.511E+08	-1.52E+01	+	+	+	+
2.928E+08	-1.52E+01	+	+	+	+
3.414E+08	-1.52E+01	+	+	+	+
3.981E+08	-1.53E+01	+	+	+	+
4.641E+08	-1.54E+01	+	+	+	+
5.411E+08	-1.56E+01	+	+	+	+
6.309E+08	-1.57E+01	+	+	+	+
7.356E+08	-1.60E+01	+	+	+	+
8.577E+08	-1.62E+01	+	+	+	+
1.000E+09	-1.66E+01	+	+	+	+
1.165E+09	-1.71E+01	+	+	+	+

```

NMOS AMP
VDD 1 0 5V
M2 1 1 2 0 NMOS2 W=4U L=1U
M1 2 3 0 0 NMOS W=100U L=1U
CLOAD 2 0 100PF
RS 4 3 1K
VI 4 0 1.5V AC
.PLOT AC VDB(2)
.PLOT AC VP(2)
.AC DEC 15 1MEG 2GIG
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=80PF CBS=80PF
.MODEL NMOS2 NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=3.2PF CBS=3.2PF
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** AC ANALYSIS

TNOM= 27.000 TEMP= 27.000

FREQ	VDB(2)				
(A)		-1.500E+01	-5.000E+00	0.	5.000E+00
2.928E+06	2.29E-01	+	+	+	+
3.414E+06	2.29E-01	+	+	+	+
3.981E+06	2.29E-01	+	+	+	+
4.641E+06	2.28E-01	+	+	+	+
5.411E+06	2.28E-01	+	+	+	+
6.309E+06	2.28E-01	+	+	+	+
7.356E+06	2.28E-01	+	+	+	+
8.577E+06	2.27E-01	+	+	+	+
1.000E+07	2.27E-01	+	+	+	+
1.165E+07	2.26E-01	+	+	+	+
1.359E+07	2.25E-01	+	+	+	+
1.584E+07	2.24E-01	+	+	+	+
1.847E+07	2.22E-01	+	+	+	+
2.154E+07	2.19E-01	+	+	+	+
2.511E+07	2.16E-01	+	+	+	+
2.928E+07	2.11E-01	+	+	+	+
3.414E+07	2.04E-01	+	+	+	+
3.981E+07	1.96E-01	+	+	+	+
4.641E+07	1.84E-01	+	+	+	+
5.411E+07	1.68E-01	+	+	+	+
6.309E+07	1.46E-01	+	+	+	+
7.356E+07	1.16E-01	+	+	+	+
8.577E+07	7.64E-02	+	+	+	+
1.000E+08	2.29E-02	+	+	+	+
1.165E+08	4.89E-02	+	+	+	+
1.359E+08	1.45E-01	+	+	+	+
1.584E+08	2.72E-01	+	+	+	+
1.847E+08	4.39E-01	+	+	+	+
2.154E+08	6.56E-01	+	+	+	+
2.511E+08	9.36E-01	+	+	+	+
2.928E+08	1.29E+00	+	+	+	+
3.414E+08	1.73E+00	+	+	+	+
3.981E+08	2.26E+00	+	+	+	+
4.641E+08	2.91E+00	+	+	+	+

7-46

```

NMOS AMP
VDD 1 0 5V
M2 1 1 2 0 NMOS2 W=4U L=1U
M1 2 3 0 0 NMOS W=100U L=1U
CLOAD 2 0 100PF
RS 4 3 1K
VI 4 0 2V AC
.PLOT AC VDB(2)
.PLOT AC VP(2)
.AC DEC 15 1MEG 2GIG
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=80FF CBS=80FF
.MODEL NMOS2 NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=3.2FF CBS=3.2FF
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** AC ANALYSIS THOM= 27.000 TEMP= 27.000

FREQ	VDB(2)					
(A)		-2.500E+01	-2.000E+01	-1.500E+01	-1.000E+01	-5.000E+00
2.511E+07	-1.31E+01	+	+	+	A	+
2.928E+07	-1.31E+01	+	+	+	A	+
3.414E+07	-1.31E+01	+	+	+	A	+
3.981E+07	-1.31E+01	+	+	+	A	+
4.641E+07	-1.31E+01	+	+	+	A	+
5.411E+07	-1.31E+01	+	+	+	A	+
6.309E+07	-1.31E+01	+	+	+	A	+
7.356E+07	-1.31E+01	+	+	+	A	+
8.577E+07	-1.32E+01	+	+	+	A	+
1.000E+08	-1.32E+01	+	+	+	A	+
1.165E+08	-1.32E+01	+	+	+	A	+
1.359E+08	-1.33E+01	+	+	+	A	+
1.584E+08	-1.34E+01	+	+	+	A	+
1.847E+08	-1.34E+01	+	+	+	A	+
2.154E+08	-1.36E+01	+	+	+	A	+
2.511E+08	-1.37E+01	+	+	+	A	+
2.928E+08	-1.40E+01	+	+	+	A	+
3.414E+08	-1.42E+01	+	+	+	A	+
3.981E+08	-1.46E+01	+	+	+	A	+
4.641E+08	-1.50E+01	+	+	+	A	+
5.411E+08	-1.55E+01	+	+	+	A	+
6.309E+08	-1.61E+01	+	+	+	A	+
7.356E+08	-1.68E+01	+	+	+	A	+

```

NMOS AMP
VDD 1 0 5V
M2 1 1 2 0 NMOS2 W=4U L=1U
M1 2 3 0 0 NMOS W=100U L=1U
CLOAD 2 0 100PF
RS 4 3 1K
VI 4 0 3V AC
.PLOT AC VDB(2)
.PLOT AC VP(2)
.AC DEC 15 1MEG 2GIG
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=80FF CBS=80FF
.MODEL NMOS2 NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=3.2FF CBS=3.2FF
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** AC ANALYSIS THOM= 27.000 TEMP= 27.000

FREQ	VDB(2)					
(A)		-3.000E+01	-2.800E+01	-2.600E+01	-2.400E+01	-2.200E+01
4.641E+07	-2.38E+01	+	+	+	+	A
5.411E+07	-2.38E+01	+	+	+	+	A
6.309E+07	-2.38E+01	+	+	+	+	A
7.356E+07	-2.38E+01	+	+	+	+	A
8.577E+07	-2.38E+01	+	+	+	+	A
1.000E+08	-2.38E+01	+	+	+	+	A
1.165E+08	-2.38E+01	+	+	+	+	A
1.359E+08	-2.39E+01	+	+	+	+	A
1.584E+08	-2.39E+01	+	+	+	+	A
1.847E+08	-2.40E+01	+	+	+	+	A
2.154E+08	-2.41E+01	+	+	+	+	A
2.511E+08	-2.42E+01	+	+	+	+	A
2.928E+08	-2.43E+01	+	+	+	+	A
3.414E+08	-2.45E+01	+	+	+	+	A
3.981E+08	-2.47E+01	+	+	+	+	A
4.641E+08	-2.50E+01	+	+	+	+	A
5.411E+08	-2.53E+01	+	+	+	+	A
6.309E+08	-2.57E+01	+	+	+	+	A
7.356E+08	-2.61E+01	+	+	+	+	A
8.577E+08	-2.65E+01	+	+	+	+	A
1.000E+09	-2.70E+01	+	+	+	+	A

7-47

```

NMOS AMP
VDD 1 0 5V
M2 1 1 2 0 NMOS2 W=4U L=1U
M1 2 3 0 0 NMOS W=100U L=1U
CLOAD 2 0 100PF
RS 4 3 1K
VI 4 0 4V AC
.PLOT AC VDB(2)
.PLOT AC VP(2)
.AC DEC 15 1MEG 2GIG
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=80FF CBS=80FF
.MODEL NMOS2 NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=3.2FF CBS=3.2FF
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** AC ANALYSIS

TNUM= 27.000 TEMP= 27.000

FREQ	VDB(2)						
(A)		-3.800E+01	-3.600E+01	-3.400E+01	-3.200E+01	-3.000E+01	
4.641E+07	-3.00E+01	+	+	+	+	+	A
5.411E+07	-3.00E+01	+	+	+	+	+	A
6.309E+07	-3.00E+01	+	+	+	+	+	A
7.356E+07	-3.00E+01	+	+	+	+	+	A
8.577E+07	-3.00E+01	+	+	+	+	+	A
1.000E+08	-3.00E+01	+	+	+	+	+	A
1.165E+08	-3.01E+01	+	+	+	+	+	A
1.359E+08	-3.01E+01	+	+	+	+	+	A
1.584E+08	-3.01E+01	+	+	+	+	+	A
1.847E+08	-3.01E+01	+	+	+	+	+	A
2.154E+08	-3.02E+01	+	+	+	+	+	A
2.511E+08	-3.02E+01	+	+	+	+	+	A
2.928E+08	-3.03E+01	+	+	+	+	+	A
3.414E+08	-3.04E+01	+	+	+	+	+	A
3.981E+08	-3.05E+01	+	+	+	+	+	A
4.641E+08	-3.07E+01	+	+	+	+	+	A
5.411E+08	-3.08E+01	+	+	+	+	+	A
6.309E+08	-3.10E+01	+	+	+	+	+	A
7.356E+08	-3.12E+01	+	+	+	+	+	A
8.577E+08	-3.14E+01	+	+	+	+	+	A
1.000E+09	-3.16E+01	+	+	+	+	+	A
1.165E+09	-3.18E+01	+	+	+	+	+	A
1.359E+09	-3.19E+01	+	+	+	+	+	A
1.584E+09	-3.21E+01	+	+	+	+	+	A
1.847E+09	-3.22E+01	+	+	+	+	+	A
2.154E+09	-3.23E+01	+	+	+	+	+	A
2.511E+09	-3.24E+01	+	+	+	+	+	A
2.928E+09	-3.25E+01	+	+	+	+	+	A
3.414E+09	-3.26E+01	+	+	+	+	+	A
3.981E+09	-3.28E+01	+	+	+	+	+	A
4.641E+09	-3.29E+01	+	+	+	+	+	A
5.411E+09	-3.31E+01	+	+	+	+	+	A
6.309E+09	-3.33E+01	+	+	+	+	+	A
7.356E+09	-3.35E+01	+	+	+	+	+	A

```

NMOS AMP
VDD 1 0 5V
M2 1 1 2 0 NMOS2 W=4U L=1U
M1 2 3 0 0 NMOS W=100U L=1U
CLOAD 2 0 100PF
RS 4 3 1K
VI 4 0 5V AC
.PLOT AC VDB(2)
.PLOT AC VP(2)
.AC DEC 15 1MEG 2GIG
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=80FF CBS=80FF
.MODEL NMOS2 NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=3.2FF CBS=3.2FF
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** AC ANALYSIS

TNUM= 27.000 TEMP= 27.000

FREQ	VDB(2)						
(A)		-6.000E+01	-5.000E+01	-4.000E+01	-3.000E+01	-2.000E+01	
3.414E+08	-3.46E+01	+	+	+	+	+	A
3.981E+08	-3.46E+01	+	+	+	+	+	A
4.641E+08	-3.46E+01	+	+	+	+	+	A
5.411E+08	-3.46E+01	+	+	+	+	+	A
6.309E+08	-3.46E+01	+	+	+	+	+	A
7.356E+08	-3.46E+01	+	+	+	+	+	A
8.577E+08	-3.46E+01	+	+	+	+	+	A
1.000E+09	-3.46E+01	+	+	+	+	+	A
1.165E+09	-3.47E+01	+	+	+	+	+	A
1.359E+09	-3.47E+01	+	+	+	+	+	A
1.584E+09	-3.47E+01	+	+	+	+	+	A
1.847E+09	-3.47E+01	+	+	+	+	+	A
2.154E+09	-3.47E+01	+	+	+	+	+	A
2.511E+09	-3.47E+01	+	+	+	+	+	A
2.928E+09	-3.48E+01	+	+	+	+	+	A
3.414E+09	-3.48E+01	+	+	+	+	+	A
3.981E+09	-3.49E+01	+	+	+	+	+	A
4.641E+09	-3.50E+01	+	+	+	+	+	A
5.411E+09	-3.51E+01	+	+	+	+	+	A
6.309E+09	-3.52E+01	+	+	+	+	+	A
7.356E+09	-3.54E+01	+	+	+	+	+	A
8.577E+09	-3.56E+01	+	+	+	+	+	A
1.000E+10	-3.59E+01	+	+	+	+	+	A
1.165E+10	-3.62E+01	+	+	+	+	+	A
1.359E+10	-3.67E+01	+	+	+	+	+	A
1.584E+10	-3.72E+01	+	+	+	+	+	A
1.847E+10	-3.79E+01	+	+	+	+	+	A
2.154E+10	-3.86E+01	+	+	+	+	+	A
2.511E+10	-3.95E+01	+	+	+	+	+	A

7.38

$$m_3, m_4 \quad I_D = \frac{\mu C_{ox}}{2} \frac{W}{L} (V_{GS} - V_t)^2$$

$$100\mu = 15\mu \cdot 50 (V_{GS} - V_t)^2$$

$$V_{GS} = -1.065 V$$

m_2, m_6, m_7

$$100\mu = 30\mu \cdot 50 (V_{GS} - V_t)^2$$

$$V_{GS} = 0.958 V$$

$$V_{GS5} = 5 - 1.065 - 0.958$$

$$= 2.977 V$$

$$100\mu = 15\mu \frac{W}{L} (2.977 - 0.7)^2$$

$$m_5 \frac{W}{L} = 1.286 = \frac{2.57\mu}{2\mu}$$

$$2.5 = V_{GS1} + V_{GS2}$$

$$2.5 - 0.958 = 1.542 V = V_{GS1}$$

$$V_{t1} = V_{t0} + \gamma (\sqrt{2\phi_f + V_{SB}} - \sqrt{2\phi_f})$$

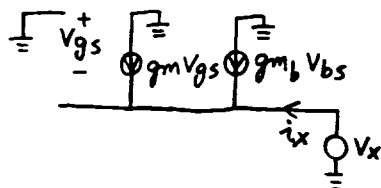
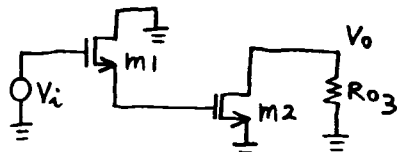
$$= 0.7 + 0.4 (\sqrt{0.6 + 0.958} - \sqrt{0.6})$$

$$= 0.89$$

$$I_{D1} = 100\mu = 30\mu \left(\frac{W}{L}\right)_1 (1.542 - 0.89)^2$$

$$\left(\frac{W}{L}\right)_1 = 7.83 = \frac{15.7\mu}{2\mu}$$

signal path



7-48

$$V_{GS} = -V_X = V_{BS}$$

$$i_X = g_m V_X + g_{mb} V_X$$

$$R_{O1} = \frac{V_X}{i_X} = \frac{1}{g_m + g_{mb}}$$

$$r_{O2} = r_{O3} = \frac{1}{0.03(100\mu)} = 333 k$$

$$R_{O3} = r_{O2} \parallel r_{O3} = 167 k$$

$$g_{m1} = \sqrt{2 I_D \mu C_{ox} \frac{W}{L}}$$

$$= \sqrt{200\mu \cdot 60\mu \cdot 7.83}$$

$$= 307 \mu A/V$$

$$g_{mb1} = g_{m1} \frac{\gamma}{2\sqrt{2\phi_f + V_{SB}}}$$

$$= 307 \mu \frac{0.4}{2\sqrt{0.6 + 0.958}}$$

$$= 49.2 \mu A/V$$

$$R_{O1} = 2811 \Omega$$

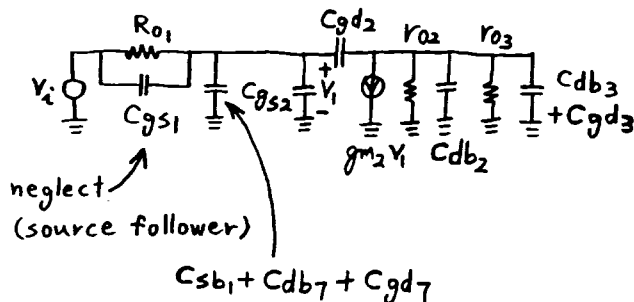
$$g_{m2} = \sqrt{200\mu \cdot 60\mu \cdot 50}$$

$$= 775 \mu A/V$$

gain

$$\frac{V_o}{V_i} = -g_{m1} R_{O1} g_{m2} R_{O3}$$

$$= -112$$



7-49

$$C_{sb1} = \frac{C_{sb0}}{\sqrt{1 + \frac{V_{SB}}{\psi_0}}}$$

$$= \frac{0.8 \text{ f}(7.83)}{\sqrt{1 + \frac{0.958}{0.6}}} = 3.89 \text{ fF}$$

$$C_{db7} = \frac{0.8 \text{ f}(100)}{\sqrt{1 + \frac{0.958}{0.6}}} = 49.6 \text{ fF}$$

$$C_{gd7} = 0.3(100\mu) = 30 \text{ fF} = C_{gd2}$$

$$C_{gs2} = \frac{2}{3} WL C_{ox} + 30 \text{ fF}$$

$$= 231 + 30$$

$$= 261 \text{ fF}$$

$$C_{db2} = \frac{C_{sb0}}{\sqrt{1 + \frac{V_{SB}}{\psi_0}}}$$

$$= \frac{0.8 \text{ f}(100)}{\sqrt{1 + \frac{2.5}{0.6}}}$$

$$= 35.2 \text{ fF} = C_{db3}$$

$$R_0(C_{sb1} + C_{db7} + C_{gd7} + C_{gs2})$$

$$= 2811(3.89 + 49.6 + 30 + 261) \text{ f}$$

$$= 0.968 \text{ ns}$$

$$(r_{o2} || r_{o3})(C_{db2} + C_{db3} + C_{gd3})$$

$$= 167 \text{ k}(35.2 + 35.2 + 30) \text{ f}$$

$$= 16.8 \text{ ns}$$

$$C_{gd2}(R_{o1} + R_{o3} + g_{m2} R_{o1} R_{o3})$$

$$= 30 \text{ f}(2811 + 167 \text{ k} + 775\mu 167 \text{ k} 2811)$$

$$= 16 \text{ ns}$$

$$f_{-3\text{dB}} = \frac{1}{2\pi} \frac{10^9}{0.968 + 16.8 + 16} = 4.71 \text{ MHz}$$

7-50

CMOS AMP

VDD 1 0 5V

M1 2 8 6 0 NMOS1 W=15.7U L=2U

M2 7 6 0 0 NMOS W=100U L=2U

M3 7 2 1 1 PMOS W=100U L=2U

M4 2 2 1 1 PMOS W=100U L=2U

M5 5 5 2 2 PMOS5 W=2.57U L=2U

M6 5 5 0 0 NMOS W=100U L=2U

M7 6 5 0 0 NMOS W=100U L=2U

VI 8 0 2.5746V AC

.PLOT AC VDB(7)

.AC DEC 20 100K 100MEG

.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0.03 LD=0 GAMMA=0.4

+ TOX=20NM CGSO=300PF CGDO=300PF CBD=80FF CBS=80FF

.MODEL NMOS1 NMOS KP=60U VTO=0.7 LAMBDA=0.03 LD=0 GAMMA=0.4

+ TOX=20NM CGSO=300PF CGDO=300PF CBD=12.6FF CBS=12.6FF

.MODEL PMOS PMOS KP=30U VTO=-0.7 LAMBDA=0.03 LD=0 GAMMA=0.4

+ TOX=20NM CGSO=300PF CGDO=300PF CBD=80FF CBS=80FF

.MODEL PMOS5 PMOS KP=30U VTO=-0.7 LAMBDA=0.03 LD=0 GAMMA=0.4

+ TOX=20NM CGSO=300PF CGDO=300PF CBD=2.06FF CBS=2.06FF

.OPTIONS NOPAGE NOMOD

.WIDTH OUT=80

.OPTIONS SPICE

.OP

.END

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

+0:1 = 5.000E+00 0:2 = 3.800E+00 0:5 = 9.504E-01

+0:6 = 1.053E+00 0:7 = 2.493E+00 0:8 = 2.574E+00

**** MOSFETS

ELEMENT	0:M1	0:M2	0:M3	0:M4	0:M5	0:M6
MODEL	0:NMOS1	0:NMOS	0:PMOS	0:PMOS	0:PMOS5	0:NMOS
ID	9.703E-05	2.011E-04	-2.011E-04	-1.938E-04	-9.674E-05	9.674E-05
IBS	-1.053E-14	0.	0.	0.	0.	0.
IRD	-3.801E-14	-2.493E-14	2.507E-14	1.199E-14	2.850E-14	-9.504E-15
VGS	1.521E+00	1.053E+00	-1.199E+00	-1.199E+00	-2.850E+00	9.504E-01
VDS	2.747E+00	2.493E+00	-2.507E+00	-1.199E+00	-2.850E+00	9.504E-01
VBS	-1.053E+00	0.	0.	0.	0.	0.
VTH	9.045E-01	7.000E-01	-7.000E-01	-7.000E-01	-7.000E-01	7.000E-01
VDSAT	6.170E-01	3.532E-01	-4.994E-01	-4.994E-01	-2.150E+00	2.504E-01
BETA	5.098E-04	3.224E-03	1.613E-03	1.554E-03	4.185E-05	3.086E-03
GAM EFF	4.000E-01	4.000E-01	4.000E-01	4.000E-01	4.000E-01	4.000E-01
GM	3.145E-04	1.139E-03	8.054E-04	7.760E-04	8.998E-05	7.726E-04
GDS	2.689E-06	5.613E-06	5.611E-06	5.611E-06	2.673E-06	2.822E-06
GMB	4.893E-05	2.940E-04	2.080E-04	2.004E-04	2.323E-05	1.995E-04
CDTOT	1.016E-14	7.058E-14	7.058E-14	8.116E-14	1.769E-15	8.452E-14
CGTOT	4.599E-14	2.952E-13	2.941E-13	2.935E-13	7.509E-15	2.959E-13
CSTOT	4.913E-14	3.402E-13	3.402E-13	3.402E-13	8.747E-15	3.402E-13
CBTOT	1.376E-14	1.232E-13	1.221E-13	1.333E-13	3.041E-15	1.393E-13
CGS	4.085E-14	2.602E-13	2.602E-13	2.602E-13	6.687E-15	2.602E-13
CGD	4.909E-15	3.115E-14	3.115E-14	3.055E-14	8.047E-16	3.044E-14

ELEMENT 0:M7

MODEL 0:NMOS

ID 9.703E-05

IBS 0.

IRD -1.053E-14

VGS 9.504E-01

VDS 1.053E+00

VBS 0.

VTH 7.000E-01

VDSAT 2.504E-01

BETA 3.095E-03

GAM EFF 4.000E-01

GM 7.750E-04

GDS 2.822E-06

GMB 2.001E-04

CDTOT 8.305E-14

CGTOT 2.959E-13

CSTOT 3.402E-13

CBTOT 1.378E-13

CGS 2.602E-13

CGD 3.048E-14

***** AC ANALYSIS

THOM= 27.000 TEMP= 27.000

FREQ	VDB(7)	1.000E+01	2.002E+01	3.000E+01	4.000E+01	5.000E+01
1.000E+05	3.87E+01	+	+	+	+	+
1.122E+05	3.87E+01	+	+	+	+	+
1.258E+05	3.87E+01	+	+	+	+	+
1.412E+05	3.87E+01	+	+	+	+	+
1.584E+05	3.87E+01	+	+	+	+	+
1.778E+05	3.87E+01	+	+	+	+	+
1.995E+05	3.87E+01	+	+	+	+	+
2.238E+05	3.87E+01	+	+	+	+	+
2.511E+05	3.87E+01	+	+	+	+	+
2.818E+05	3.87E+01	+	+	+	+	+
3.162E+05	3.87E+01	+	+	+	+	+
3.548E+05	3.87E+01	+	+	+	+	+
3.981E+05	3.87E+01	+	+	+	+	+
4.466E+05	3.87E+01	+	+	+	+	+
5.011E+05	3.87E+01	+	+	+	+	+
5.623E+05	3.86E+01	+	+	+	+	+
6.309E+05	3.86E+01	+	+	+	+	+
7.079E+05	3.86E+01	+	+	+	+	+
7.943E+05	3.86E+01	+	+	+	+	+
8.912E+05	3.86E+01	+	+	+	+	+
9.999E+05	3.86E+01	+	+	+	+	+
1.122E+06	3.85E+01	+	+	+	+	+
1.258E+06	3.85E+01	+	+	+	+	+
1.412E+06	3.85E+01	+	+	+	+	+
1.584E+06	3.84E+01	+	+	+	+	+
1.778E+06	3.84E+01	+	+	+	+	+
1.995E+06	3.83E+01	+	+	+	+	+
2.238E+06	3.82E+01	+	+	+	+	+
2.511E+06	3.81E+01	+	+	+	+	+
2.818E+06	3.79E+01	+	+	+	+	+
3.162E+06	3.77E+01	+	+	+	+	+
3.548E+06	3.75E+01	+	+	+	+	+
3.981E+06	3.73E+01	+	+	+	+	+
4.466E+06	3.70E+01	+	+	+	+	+
5.011E+06	3.66E+01	+	+	+	+	+
5.623E+06	3.62E+01	+	+	+	+	+
6.309E+06	3.57E+01	+	+	+	+	+
7.079E+06	3.52E+01	+	+	+	+	+
7.943E+06	3.46E+01	+	+	+	+	+
8.912E+06	3.40E+01	+	+	+	+	+
9.999E+06	3.33E+01	+	+	+	+	+
1.122E+07	3.26E+01	+	+	+	+	+
1.258E+07	3.18E+01	+	+	+	+	+
1.412E+07	3.10E+01	+	+	+	+	+
1.584E+07	3.01E+01	+	+	+	+	+
1.778E+07	2.92E+01	+	+	+	+	+
1.995E+07	2.83E+01	+	+	+	+	+
2.238E+07	2.74E+01	+	+	+	+	+
2.511E+07	2.64E+01	+	+	+	+	+
2.818E+07	2.55E+01	+	+	+	+	+
3.162E+07	2.45E+01	+	+	+	+	+
3.548E+07	2.35E+01	+	+	+	+	+
3.981E+07	2.24E+01	+	+	+	+	+
4.466E+07	2.14E+01	+	+	+	+	+
5.011E+07	2.03E+01	+	+	+	+	+
5.623E+07	1.93E+01	+	+	+	+	+
6.309E+07	1.82E+01	+	+	+	+	+
7.079E+07	1.70E+01	+	+	+	+	+
7.943E+07	1.58E+01	+	+	+	+	+
8.912E+07	1.46E+01	+	+	+	+	+
9.999E+07	1.34E+01	+	+	+	+	+

7.39

$$I_{C1} = 261 \mu A$$

$$V_{C1} = 5 - 2.61 = 2.39$$

$$V_{B1} = V_{GS2} + V_{BE2}$$

$$= 1.47 + 0.8 = 2.27$$

$$V_{BC1} \approx 0$$

$$\therefore C_{\mu 1} = 5 \text{ fF}$$

$$C_{\pi 1} = C_{je} + \tau_F g_m$$

$$= 2(5 \text{ f}) + 10 \text{ p} \frac{0.261 \text{ m}}{V_T}$$

$$= 110 \text{ fF}$$

$$C_{cs1} = \frac{20 \text{ f}}{\left(1 + \frac{2.39}{0.6}\right)^{0.33}}$$

$$= 11.8 \text{ fF}$$

$$I_{C3} = 1.59 \text{ mA}$$

$$C_{\pi 3} = 10 \text{ f} + 10 \text{ p} \frac{1.59}{26}$$

$$= 622 \text{ fF}$$

$$V_{CB3} = 2.61 \text{ V}$$

$$C_{\mu 3} = \frac{5 \text{ f}}{\left(1 + \frac{2.61}{0.6}\right)^{0.33}}$$

$$= 2.87 \text{ fF}$$

$$R_{\pi 03} = r_{\pi 3} \parallel \frac{R_S + r_{b3} + R_{E3}}{1 + g_{m3} R_{E3}}$$

$$r_{\pi 3} = \frac{\beta}{g_m} = 1.96 \text{ k}$$

$$R_S = R_{L2} = 10 \text{ k}$$

$$r_{b3} = 400$$

$$R_{E3} = 1 \text{ k} \parallel 30 \text{ k} = 968$$

$$R_{\pi 03} = 1.96 \text{ k} \parallel 189$$

$$= 172 \Omega$$

7-51

$$R_{\pi 03} C_{\pi 3} = 172 (622 \text{ f}) = 107 \text{ ps}$$

@ Q_1 collector

$$C_1 = C_{\mu 1} + C_{\mu 3} + C_{cs1}$$

$$= 5 + 2.87 + 11.8$$

$$= 19.7 \text{ fF}$$

$$R_1 = R_{L2} \parallel R_{i3}$$

$$= 10 \text{ k} \parallel r_{\pi 3} (1 + g_{m3} R_{E3})$$

$$= 10 \text{ k} \parallel 118 \text{ k}$$

$$= 9.22 \text{ k}$$

$$R_1 C_1 = 182 \text{ ps}$$

dominant pole

$$|P_1| = \frac{1}{182 \text{ p} + 107 \text{ p}} = 3.46 \text{ G rad/s}$$

$$\rightarrow 551 \text{ MHz}$$

@ m1 drain

$$C_2 = C_{db1} + C_{gd1} + C_{\pi 1}$$

$$= 200 + 90 + 110$$

$$= 400 \text{ fF}$$

$$R_2 = R_{L1} \parallel \left(\frac{1}{g_{m1}} + \frac{R_{S1}}{\beta} + r_{e1} \right)$$

$$g_{mQ2} = \frac{273 \mu}{26 \text{ m}} = 10.5 \text{ mA/V}$$

$$g_{m2} = \sqrt{2(273 \mu)(40 \mu)(30)}$$

$$= 809 \mu \text{A/V}$$

$$R_{S1} = 10 \text{ k} \parallel \left(\frac{1}{g_{mQ2}} + \frac{1}{g_{m2}} \right)$$

$$= 1.17 \text{ k}$$

$$R_2 = 1 \text{ k} \parallel \left(99.6 + \frac{1.17 \text{ k}}{120} + 40 \right)$$

$$= 130$$

$$\text{second pole } |P_2| = \frac{1}{R_2 C_2} = 19.2 \text{ G rad/s}$$

$$\rightarrow 3.06 \text{ GHz}$$

7-52

```

BICMOS AMP
VCC 1 0 5V
RL1 1 4 1K
M1 4 2 0 0 NMOS W=300U L=1U
V1 2 0 1.59V AC
.TF V(7) V1
RF 2 7 30K
RE 7 0 1K
RL2 1 3 10K
RBIAS 1 5 10K
Q1 3 5 4 NPN
Q2 5 5 6 NPN
Q3 1 3 7 NPN
M2 6 6 0 0 NMOS2 W=300U L=1U
.MODEL NMOS NMOS KP=40U VTO=0.8 LAMBDA=0 LD=0 GAMMA=0
+ TOX=34.5NM CBD=340FF CBS=200FF CGSO=300PF CGDO=300PF
.MODEL NMOS2 NMOS2 KP=40U VTO=0.8 LAMBDA=0 LD=0 GAMMA=0
+ TOX=34.5NM CBD=34FF CBS=20FF CGSO=300PF CGDO=300PF
.MODEL NPN NPN IS=6E-18 BF=120 RB=400 VAF=35V
+ CJE=5FF CJC=5FF CJS=20FF TF=10PS
+ MJT=0.4 MJC=0.33 MJS=0.33 RE=40
+ VJE=0.8 VJC=0.6 VJS=0.6 RC=100
.AC DEC 20 10MEG 10GIG
.PLOT AC VP(7)
.OPTIONS NOFAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

```

+0:1      = 5.000E+00 0:2      = 1.590E+00 0:3      = 2.669E+00
+0:4      = 1.476E+00 0:5      = 2.293E+00 0:6      = 1.469E+00
+0:7      = 1.734E+00

```

**** BIPOLAR JUNCTION TRANSISTORS

```

ELEMENT 0:Q1      0:Q2      0:Q3
MODEL   0:NPN     0:NPN     0:NPN
IB      1.811E-06  2.223E-06  1.355E-05
IC      2.195E-04  2.666E-04  1.726E-03
VBE     8.171E-01  8.244E-01  9.346E-01
VCE     1.192E+00  8.244E-01  3.265E+00
VBC     -3.757E-01  0.      -2.330E+00
VS      -2.647E+00 -2.267E+00 -4.827E+00
POWER   2.633E-04  2.216E-04  5.649E-03
BETAD   1.212E+02  1.199E+02  1.274E+02
GM       8.480E-03  1.030E-02  6.670E-02
RPI      1.428E+04  1.163E+04  1.909E+03
RX       4.000E+02  4.000E+02  4.000E+02
RO      1.610E+05  1.311E+05  2.152E+04
CPI      9.415E-14  1.124E-13  6.771E-13
CMU      4.290E-15  5.073E-15  3.021E-15
CBX      0.      0.      0.
CCS      1.146E-14  1.194E-14  9.670E-15
BETAAC   1.211E+02  1.198E+02  1.273E+02
FT       1.371E+10  1.395E+10  1.560E+10

```

**** MOSFETS

```

ELEMENT 0:M1      0:M2
MODEL   0:NMOS    0:NMOS2
ID      3.745E-03  2.688E-04
IBS     0.      0.
IBD     -1.477E-14 -1.469E-14
VGS     1.590E+00  1.469E+00
VDS     1.476E+00  1.469E+00
VBS     0.      0.
VTH     8.000E-01  8.000E-01
VDSAT   7.900E-01  6.693E-01
BETA    1.200E-02  1.200E-03
GAM EFF 0.      0.
GM       9.480E-03  8.032E-04
GDS     0.      0.
GMB     0.      0.
CUTOT   2.921E-13  2.925E-14
CGTOT   3.863E-13  3.875E-14
CSTOT   4.902E-13  4.902E-14
CBTOT   4.071E-13  4.086E-14
CGS     2.902E-13  2.902E-14
CGD     9.059E-14  9.059E-15

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(7)/V1      = -6.966E+01
INPUT RESISTANCE AT V1      = 4.245E+02
OUTPUT RESISTANCE AT V(7)   = 1.187E+02

```

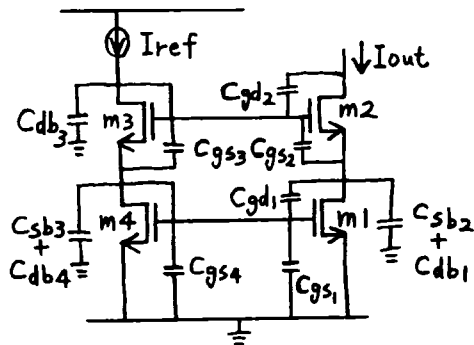
***** AC ANALYSIS

TNOM= 27.000 TEMP= 27.000

FREQ (A)	VP(7) -1.000E+02	0.	1.000E+02	2.000E+02	3.000E+02
1.000E+07	1.78E+02	+	+	+	+
1.122E+07	1.78E+02	+	+	+	+
1.258E+07	1.78E+02	+	+	+	+
1.412E+07	1.77E+02	+	+	+	+
1.584E+07	1.77E+02	+	+	+	+
1.778E+07	1.77E+02	+	+	+	+
1.995E+07	1.77E+02	+	+	+	+
2.238E+07	1.76E+02	+	+	+	+
2.511E+07	1.76E+02	+	+	+	+
2.818E+07	1.75E+02	+	+	+	+
3.162E+07	1.75E+02	+	+	+	+
3.548E+07	1.74E+02	+	+	+	+
3.981E+07	1.74E+02	+	+	+	+
4.466E+07	1.73E+02	+	+	+	+
5.011E+07	1.72E+02	+	+	+	+
5.623E+07	1.71E+02	+	+	+	+
6.309E+07	1.70E+02	+	+	+	+
7.079E+07	1.69E+02	+	+	+	+
7.943E+07	1.68E+02	+	+	+	+
8.912E+07	1.67E+02	+	+	+	+
9.999E+07	1.65E+02	+	+	+	+
1.122E+08	1.63E+02	+	+	+	+
1.258E+08	1.61E+02	+	+	+	+
1.412E+08	1.59E+02	+	+	+	+
1.584E+08	1.57E+02	+	+	+	+
1.778E+08	1.54E+02	+	+	+	+
1.995E+08	1.51E+02	+	+	+	+
2.238E+08	1.48E+02	+	+	+	+
2.511E+08	1.44E+02	+	+	+	+
2.818E+08	1.41E+02	+	+	+	+
3.162E+08	1.38E+02	+	+	+	+
3.548E+08	1.32E+02	+	+	+	+
3.981E+08	1.27E+02	+	+	+	+
4.466E+08	1.21E+02	+	+	+	+
5.011E+08	1.16E+02	+	+	+	+
5.623E+08	1.13E+02	+	+	+	+
6.309E+08	1.04E+02	+	+	+	+
7.079E+08	9.78E+01	+	+	+	+
7.943E+08	9.13E+01	+	+	+	+
8.912E+08	8.47E+01	+	+	+	+
9.999E+08	7.79E+01	+	+	+	+
1.122E+09	7.12E+01	+	+	+	+
1.258E+09	6.44E+01	+	+	+	+
1.412E+09	5.77E+01	+	+	+	+
1.584E+09	5.11E+01	+	+	+	+
1.778E+09	4.45E+01	+	+	+	+
1.995E+09	3.79E+01	+	+	+	+
2.238E+09	3.14E+01	+	+	+	+
2.511E+09	2.49E+01	+	+	+	+
2.818E+09	1.85E+01	+	+	+	+
3.162E+09	1.20E+01	+	+	+	+
3.548E+09	5.49E+00	+	+	+	+
3.981E+09	1.11E+00	+	+	+	+
4.466E+09	7.82E+00	+	+	+	+
5.011E+09	1.46E+01	+	+	+	+
5.623E+09	2.15E+01	+	+	+	+
6.309E+09	2.85E+01	+	+	+	+
7.079E+09	3.55E+01	+	+	+	+
7.943E+09	4.24E+01	+	+	+	+
8.912E+09	4.89E+01	+	+	+	+
9.999E+09	5.49E+01	+	+	+	+

dominant pole at 135° phase = 316 MHz
 second pole at 45° phase = 1.8 GHz

7-40



All $I_D = 100 \mu A$

sum time constants

$$T_1 = (C_{gs4} + C_{gs1}) \frac{1}{g_{m4}}$$

$$g_{m4} = \sqrt{2 I_D \mu C_{ox} \frac{W}{L}}$$

$$= \sqrt{200 \mu 60 \mu 10}$$

$$= 346 \mu$$

$$T_1 = 40 f \cdot 2887$$

$$= 115 ps$$

drain of m4

$$T_2 = (C_{db4} + C_{sb3}) \frac{1}{g_{m4}}$$

$$= (10 fF + 10 fF) \cdot 2887$$

$$= 57.7 ps$$

drain of m3

$$T_3 = (C_{db3} + C_{gd2}) \left(\frac{1}{g_{m3}} + \frac{1}{g_{m4}} \right)$$

$$= (10 + 3) f (2) (2887)$$

$$= 75.1 ps$$

gate-source of m3

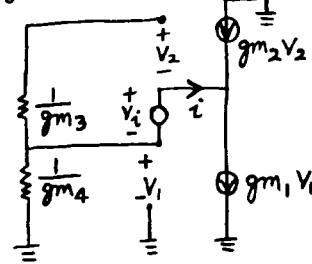
$$T_4 = C_{gs3} \frac{1}{g_{m3}}$$

$$= 20 f \cdot 2887$$

$$= 57.7 ps$$

7-53

gate-drain of m1



$$g_{m2} V_2 + i = g_{m1} V_1 = - \frac{g_{m1}}{g_{m4}} i$$

$$V_1 = \frac{-i}{g_{m4}}$$

$$g_{m2} V_2 + 2i = 0$$

$$V_2 = -V_1$$

$$-g_{m2} V_1 + 2i = 0$$

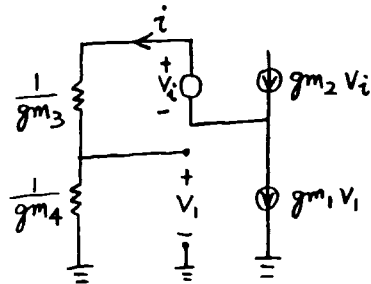
$$R_i = \frac{V_1}{i} = \frac{2}{g_{m2}}$$

$$T_5 = C_{gd1} \frac{2}{g_m}$$

$$= 3 f (2) (2887)$$

$$= 17.3 ps$$

gate-source of m2



$$V_1 = \frac{i}{g_{m4}}$$

$$i = g_{m2} V_i - g_{m1} V_1$$

$$= g_m V_i - i$$

$$2i = g_m V_i$$

$$R_i = \frac{V_i}{i} = \frac{2}{g_m}$$

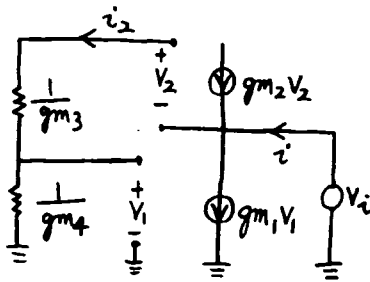
7-54

$$T_6 = C_{gs2} \frac{2}{g_m}$$

$$= 20 \text{ f}(2)(2887)$$

$$= 115 \text{ ps}$$

drain of m_1



$$i = g_{m1} V_1 - g_{m2} V_2$$

$$V_1 = V_i + V_2$$

$$i_2 = 0$$

$$V_1 = 0$$

$$0 = V_i + V_2$$

$$i = -g_{m2} (-V_i)$$

$$R_i = \frac{V_i}{i} = \frac{1}{g_{m2}}$$

$$T_7 = 20 \text{ f } 2887$$

$$= 57.7 \text{ ps}$$

$$T_0 = \sum_{n=1}^7 T_n = 496 \text{ ps}$$

dominant pole

$$|P_1| = \frac{1}{T_0} = 2.02 \text{ G rad/s}$$

$$\hookrightarrow 321 \text{ MHz}$$

device f_T

$$f_T = \frac{1}{2\pi} \frac{g_m}{C_{gs} + C_{gd}}$$

$$= \frac{1}{2\pi} \frac{1}{2887} \frac{1}{23 \text{ f}}$$

$$= 2.4 \text{ GHz}$$

7-55

```

MOS CASCODE CURRENT MIRROR
VCC 1 0 5V
IREF 1 2 100UA AC
M1 4 3 0 0 NMOS W=10U L=1U
M2 5 2 4 4 NMOS W=10U L=1U
M3 2 2 3 3 NMOS W=10U L=1U
M4 3 3 0 0 NMOS W=10U L=1U
VOOT 5 0 2.5547V
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0
+ TOX=11.5NM CBD=16.1FF CBS=10FF CGSO=300PF CGDO=300PF
.AC DEC 30 10MEG 1GIG
.PLOT AC IDB(VOOT)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

```

+0:1      = 5.000E+00 0:2      = 2.554E+00 0:3      = 1.277E+00
+0:4      = 1.277E+00 0:5      = 2.554E+00

```

**** MOSFETS

ELEMENT	0:M1	0:M2	0:M3	0:M4
MODEL	0:NMOS	0:NMOS	0:NMOS	0:NMOS
ID	1.000E-04	1.000E-04	1.000E-04	1.000E-04
IBS	0.	0.	0.	0.
IRD	-1.277E-14	-1.277E-14	-1.277E-14	-1.277E-14
VGS	1.277E+00	1.277E+00	1.277E+00	1.277E+00
VDS	1.277E+00	1.277E+00	1.277E+00	1.277E+00
VBS	0.	0.	0.	0.
VTH	7.000E-01	7.000E-01	7.000E-01	7.000E-01
VDSAT	5.774E-01	5.774E-01	5.774E-01	5.774E-01
BETA	6.000E-04	6.000E-04	6.000E-04	6.000E-04
GAM EFF	0.	0.	0.	0.
GM	3.464E-04	3.464E-04	3.464E-04	3.464E-04
GDS	0.	0.	0.	0.
GMB	0.	0.	0.	0.
CDTOT	1.304E-14	1.304E-14	1.304E-14	1.304E-14
CGTOT	2.687E-14	2.687E-14	2.687E-14	2.687E-14
CSTOT	3.302E-14	3.302E-14	3.302E-14	3.302E-14
CBTOT	2.079E-14	2.079E-14	2.079E-14	2.079E-14
CGS	2.302E-14	2.302E-14	2.302E-14	2.302E-14
CGD	3.051E-15	3.051E-15	3.051E-15	3.051E-15

***** AC ANALYSIS

THOM= 27.000 TEMP= 27.000

FREQ	IDB(VOOT)					
1.000E+07	-1.19E-03					
1.079E+07	-1.37E-03					
1.165E+07	-1.60E-03					
1.258E+07	-1.86E-03					
1.359E+07	-2.17E-03					
1.467E+07	-2.53E-03					
1.584E+07	-2.95E-03					
1.711E+07	-3.44E-03					
1.847E+07	-4.01E-03					
1.995E+07	-4.68E-03					
2.154E+07	-5.46E-03					
2.326E+07	-6.36E-03					
2.511E+07	-7.41E-03					
2.712E+07	-8.64E-03					
2.928E+07	-1.01E-02					
3.162E+07	-1.17E-02					
3.414E+07	-1.37E-02					
3.686E+07	-1.60E-02					
3.981E+07	-1.86E-02					
4.298E+07	-2.17E-02					
4.641E+07	-2.53E-02					
5.011E+07	-2.94E-02					
5.411E+07	-3.43E-02					
5.843E+07	-3.99E-02					
6.309E+07	-4.65E-02					
6.812E+07	-5.42E-02					
7.356E+07	-6.31E-02					
7.943E+07	-7.35E-02					
8.577E+07	-8.55E-02					
9.261E+07	-9.95E-02					
1.000E+08	-1.16E-01					
1.079E+08	-1.35E-01					
1.165E+08	-1.56E-01					
1.258E+08	-1.82E-01					
1.359E+08	-2.11E-01					
1.467E+08	-2.45E-01					
1.584E+08	-2.84E-01					
1.711E+08	-3.29E-01					
1.847E+08	-3.81E-01					
1.995E+08	-4.40E-01					
2.154E+08	-5.08E-01					
2.326E+08	-5.86E-01					
2.511E+08	-6.74E-01					
2.712E+08	-7.75E-01					
2.928E+08	-8.88E-01					
3.162E+08	-1.01E+00					
3.414E+08	-1.16E+00					
3.686E+08	-1.32E+00					
3.981E+08	-1.49E+00					
4.298E+08	-1.69E+00					
4.641E+08	-1.90E+00					
5.011E+08	-2.14E+00					
5.411E+08	-2.39E+00					
5.843E+08	-2.66E+00					
6.309E+08	-2.95E+00					
6.812E+08	-3.26E+00					
7.356E+08	-3.58E+00					
7.943E+08	-3.91E+00					
8.577E+08	-4.26E+00					
9.261E+08	-4.62E+00					
1.000E+09	-4.99E+00					

BANDWIDTH = 680 MEGAHERTZ

MOS CASCODE CURRENT MIRROR

```

VCC 1 0 5V
IREF 1 2 50UA AC
M1 4 3 0 0 NMOS W=10U L=1U
M2 5 2 4 4 NMOS W=10U L=1U
M3 2 2 3 3 NMOS W=10U L=1U
M4 3 3 0 0 NMOS W=10U L=1U
VOOT 5 0 2.2165V
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0
+ TOX=11.5NM CBD=16.1FF CBS=10FF CGSO=300PF CGDO=300PF
.AC DEC 30 10MEG 1GIG
.PLOT AC IDB(VOOT)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

BANDWIDTH = 460 MEGAHERTZ

7-56

```
*****
MOS CASCODE CURRENT MIRROR
VCC 1 0 5V
IREF 1 2 200UA AC
M1 4 3 0 0 NMOS W=10U L=1U
M2 5 2 4 4 NMOS W=10U L=1U
M3 2 2 3 3 NMOS W=10U L=1U
M4 3 3 0 0 NMOS W=10U L=1U
VOUT 5 0 3.0330V
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0
+ TOX=11.5NM CBD=16.1FF CBS=10FF CGSO=300FF CGDO=300FF
.AC DEC 30 10MEG 1GIG
.PLOT AC IDB(VOUT)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
*****
BANDWIDTH = 930 MEGAHERTZ
```

7.41

$$\text{all } I_D = 100 \mu A$$

$$R_{sx} = \frac{1}{E_c \mu C_{ox} W}$$

$$= \frac{1}{1.5 M \cdot 60 \mu \cdot 10 \mu}$$

$$= 1111 \Omega$$

$$m_3, m_4$$

$$\frac{1}{g_m} + R_{sx} = 2887 + 1111 = 4k$$

$$m_1, m_2$$

$$G_m = \frac{g_m}{1 + g_m R_{sx}} = \frac{\frac{1}{2887}}{1 + \frac{1111}{2887}}$$

$$= 250 \mu$$

$$\frac{1}{G_m} = \frac{1 + g_m R_{sx}}{g_m} = \frac{1}{g_m} + R_{sx}$$

$$\frac{1}{G_m} = 4k \text{ also}$$

$\therefore$ all time constants

$$\text{increase by } \frac{4000}{2887}$$

$$\text{dominant pole @ } 321 \frac{2887}{4000} M$$

$$= 232 \text{ MHz}$$

$$\text{device } f_T = \frac{1}{2\pi} \frac{1}{4000} \frac{1}{23 f}$$

$$= 1.73 \text{ GHz}$$

CMOS CASCODE CURRENT MIRROR, SHORT CHANNEL EFFECTS

```

VCC 1 0 5V
IREF 1 2 100UA AC
M1 8 4 9 9 NMOS W=10U L=1U
RSX1 9 0 1111
CGS1 4 0 20PF
M2 6 2 7 7 NMOS W=10U L=1U
RSX2 7 8 1111
CGS2 2 8 20PF
M3 2 2 3 3 NMOS W=10U L=1U
RSX3 3 4 1111
CGS3 2 4 20PF
M4 4 4 5 5 NMOS W=10U L=1U
RSX4 5 0 1111
CGS4 4 0 20PF
CSB3 4 0 10PF
CSB2 8 0 10PF
CDB1 8 0 10PF
CDB3 2 0 10PF
CDB4 4 0 10PF
VOUT 6 0 2.7769V
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0
+ TOX=11.5NM CGSO=300PF CGDO=300PF
.AC DEC 30 10MEG 1GIG
.PLOT AC IDB(VOUT)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

```

+0:1 = 5.000E+00 0:2 = 2.776E+00 0:3 = 1.499E+00
+0:4 = 1.388E+00 0:5 = 1.111E-01 0:6 = 2.776E+00
+0:7 = 1.499E+00 0:8 = 1.388E+00 0:9 = 1.111E-01

```

**** MOSFETS

ELEMENT	0:M1	0:M2	0:M3	0:M4
MODEL	0:NMOS	0:NMOS	0:NMOS	0:NMOS
ID	1.000E-04	1.000E-04	1.000E-04	1.000E-04
IBS	0.	0.	0.	0.
IBD	-1.277E-14	-1.277E-14	-1.277E-14	-1.277E-14
VGS	1.277E+00	1.277E+00	1.277E+00	1.277E+00
VDS	1.277E+00	1.277E+00	1.277E+00	1.277E+00
VBS	0.	0.	0.	0.
VTH	7.000E-01	7.000E-01	7.000E-01	7.000E-01
VDSAT	5.774E-01	5.774E-01	5.774E-01	5.774E-01
BETA	6.000E-04	6.000E-04	6.000E-04	6.000E-04
GAM KFF	0.	0.	0.	0.
GM	3.464E-04	3.464E-04	3.464E-04	3.464E-04
GDS	0.	0.	0.	0.
GMB	0.	0.	0.	0.
COTOT	3.051E-15	3.051E-15	3.051E-15	3.051E-15
CGTOT	2.687E-14	2.687E-14	2.687E-14	2.687E-14
CSTOT	2.302E-14	2.302E-14	2.302E-14	2.302E-14
CBTOT	8.005E-16	8.005E-16	8.005E-16	8.005E-16
CGS	2.302E-14	2.302E-14	2.302E-14	2.302E-14
CGD	3.051E-15	3.051E-15	3.051E-15	3.051E-15

***** AC ANALYSIS

THOM= 27.000 TEMP= 27.000

FREQ	IDB(VOUT)	-1.500E+01	-1.000E+01	-5.000E+00	0.	5.000E+00
1.000E+07	-7.63E-03	+	+	+	+	+
1.079E+07	-8.89E-03	+	+	+	+	+
1.165E+07	-1.04E-02	+	+	+	+	+
1.258E+07	-1.21E-02	+	+	+	+	+
1.359E+07	-1.41E-02	+	+	+	+	+
1.467E+07	-1.64E-02	+	+	+	+	+
1.584E+07	-1.91E-02	+	+	+	+	+
1.711E+07	-2.23E-02	+	+	+	+	+
1.847E+07	-2.60E-02	+	+	+	+	+
1.995E+07	-3.03E-02	+	+	+	+	+
2.154E+07	-3.53E-02	+	+	+	+	+
2.326E+07	-4.11E-02	+	+	+	+	+
2.511E+07	-4.79E-02	+	+	+	+	+
2.712E+07	-5.58E-02	+	+	+	+	+
2.928E+07	-6.50E-02	+	+	+	+	+
3.162E+07	-7.57E-02	+	+	+	+	+
3.414E+07	-8.82E-02	+	+	+	+	+
3.686E+07	-1.03E-01	+	+	+	+	+
3.981E+07	-1.20E-01	+	+	+	+	+
4.298E+07	-1.39E-01	+	+	+	+	+
4.641E+07	-1.62E-01	+	+	+	+	+
5.011E+07	-1.88E-01	+	+	+	+	+
5.411E+07	-2.19E-01	+	+	+	+	+
5.843E+07	-2.54E-01	+	+	+	+	+
6.309E+07	-2.95E-01	+	+	+	+	+
6.812E+07	-3.42E-01	+	+	+	+	+
7.356E+07	-3.97E-01	+	+	+	+	+
7.943E+07	-4.60E-01	+	+	+	+	+
8.577E+07	-5.32E-01	+	+	+	+	+
9.261E+07	-6.15E-01	+	+	+	+	+
1.000E+08	-7.10E-01	+	+	+	+	+
1.079E+08	-8.19E-01	+	+	+	+	+
1.165E+08	-9.43E-01	+	+	+	+	+
1.258E+08	-1.08E+00	+	+	+	+	+
1.359E+08	-1.24E+00	+	+	+	+	+
1.467E+08	-1.42E+00	+	+	+	+	+
1.584E+08	-1.62E+00	+	+	+	+	+
1.711E+08	-1.84E+00	+	+	+	+	+
1.847E+08	-2.09E+00	+	+	+	+	+
1.995E+08	-2.37E+00	+	+	+	+	+
2.154E+08	-2.68E+00	+	+	+	+	+
2.326E+08	-3.01E+00	+	+	+	+	+
2.511E+08	-3.38E+00	+	+	+	+	+
2.712E+08	-3.77E+00	+	+	+	+	+
2.928E+08	-4.20E+00	+	+	+	+	+
3.162E+08	-4.65E+00	+	+	+	+	+
3.414E+08	-5.13E+00	+	+	+	+	+
3.686E+08	-5.64E+00	+	+	+	+	+
3.981E+08	-6.18E+00	+	+	+	+	+
4.298E+08	-6.73E+00	+	+	+	+	+
4.641E+08	-7.30E+00	+	+	+	+	+
5.011E+08	-7.89E+00	+	+	+	+	+
5.411E+08	-8.48E+00	+	+	+	+	+
5.843E+08	-9.07E+00	+	+	+	+	+
6.309E+08	-9.65E+00	+	+	+	+	+
6.812E+08	-1.02E+01	+	+	+	+	+
7.356E+08	-1.07E+01	+	+	+	+	+
7.943E+08	-1.13E+01	+	+	+	+	+
8.577E+08	-1.18E+01	+	+	+	+	+
9.261E+08	-1.23E+01	+	+	+	+	+
1.000E+09	-1.27E+01	+	+	+	+	+

BANDWIDTH = 230 MEGAHERTZ

CMOS CASCODE CURRENT MIRROR, SHORT CHANNEL EFFECTS

```

VCC 1 0 5V
IREF 1 2 50UA AC
M1 8 4 9 9 NMOS W=10U L=1U
RSX1 9 0 1111
CGS1 4 0 20PF
M2 6 2 7 7 NMOS W=10U L=1U
RSX2 7 8 1111
CGS2 2 8 20PF
M3 2 2 3 3 NMOS W=10U L=1U
RSX3 3 4 1111
CGS3 2 4 20PF
M4 4 4 5 5 NMOS W=10U L=1U
RSX4 5 0 1111
CGS4 4 0 20PF
CSB3 4 0 10PF
CSB2 8 0 10PF
CDB1 8 0 10PF
CDB3 2 0 10PF
CDB4 4 0 10PF
VOUT 6 0 2.3276V
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0
+ TOX=11.5NM CGSO=300PF CGDO=300PF
.AC DEC 30 10MEG 1GIG

```

7-58

```
.PLOT AC IDB(VOUT)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

BANDWIDTH = 170 MEGAHERTZ

CMOS CASCODE CURRENT MIRROR, SHORT CHANNEL EFFECTS

```
VCC 1 0 5V
IREF 1 2 200UA AC
M1 8 4 9 9 NMOS W=10U L=1U
RSX1 9 0 1111
CGS1 4 0 20FF
M2 6 2 7 7 NMOS W=10U L=1U
RSX2 7 8 1111
CGS2 2 8 20FF
M3 2 2 3 3 NMOS W=10U L=1U
RSX3 3 4 1111
CGS3 2 4 20FF
M4 4 4 5 5 NMOS W=10U L=1U
RSX4 5 0 1111
CGS4 4 0 20FF
CSB3 4 0 10FF
CSB2 8 0 10FF
CDB1 8 0 10FF
CDB3 2 0 10FF
CDB4 4 0 10FF
VOUT 6 0 3.4774V
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0
+ TOX=11.5NM CGSO=300FF CGDO=300FF
.AC DEC 30 10MEG 1GIG
.PLOT AC IDB(VOUT)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

BANDWIDTH = 320 MEGAHERTZ

7.42

$$m_3 \quad I_D = 100 \mu A$$

$$\begin{aligned} g_m &= \sqrt{2 I_D \mu_n C_{ox} \frac{W}{L}} \\ &= \sqrt{200 \mu \cdot 60 \mu \cdot 10} \\ &= 346 \mu \frac{A}{V} \\ &= \frac{1}{2890} \Omega \end{aligned}$$

use $\frac{1}{2}$ circuit

$$\begin{aligned} T_o &= \frac{1}{g_{m3}} (C_{gs3} + C_{sb3} + C_{gd10} \\ &\quad + C_{db10} + C_{db1} + C_{gd1}) \\ &= 2890 (20 + 10 + 6 \\ &\quad + 20 + 10 + 3) f \\ &= 199 ps \end{aligned}$$

non-dominant pole

$$\frac{1}{2\pi T_o} = 799 MHz$$

SS gain

$$\frac{V_o}{V_i} = g_{m1} \frac{1}{j\omega C_L}$$

$$\begin{aligned} \omega_1 &= \frac{g_{m1}}{C_L} @ \left| \frac{V_o}{V_i} \right| = 1 \\ &= \frac{245 \mu}{1p} \end{aligned}$$

$$= 245 M rad/s$$

$$\rightarrow 39 MHz$$

$$\begin{aligned} g_{m1} &= \sqrt{2 I_D \mu_p C_{ox} \frac{W}{L}} \\ &= 245 \mu \frac{A}{V} \end{aligned}$$

7-59

from input to source of m_3

$$\text{transfer function} = \frac{K}{1 + \frac{j\omega}{2\pi 799M}}$$

$$@ \omega = \omega_1 = 245 M rad/s$$

phase from non-dominant pole

$$= -\arctan \frac{245M}{2\pi 799M}$$

$$= -2.79^\circ$$

PART OF FOLDED CASCADE

```

VDD 1 0 0 3V
VSS 2 0 -3V
M11 8 3 1 1 PMOS W=10U L=1U
V3 3 0 1.1453V
M1 7 9 8 8 PMOS W=10U L=1U
M2 15 10 8 8 PMOS W=10U L=1U
M3 18 11 17 2 NMOS W=10U L=1U
M4 16 11 18 2 NMOS W=10U L=1U
V11 11 0 -0.44565V
N9 18 12 2 2 NMOS2 W=20U L=1U
M10 17 12 2 2 NMOS2 W=20U L=1U
V12 12 0 -1.72265V
VOOT15 15 0 0V
VOOT16 16 0 0V

```

```
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0
+ TOX=11.5NM CBD=16.1FF CRS=10FF CGSO=300PF CGDO=300PF
.MODEL NMOS2 NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0
+ TOX=11.5NM CBD=327FF CRS=20FF CGSO=300PF CGDO=300PF
.MODEL PMOS PMOS KP=30U VTO=-0.7 LAMBDA=0 LD=0 GAMMA=0
+ TOX=11.5NM CBD=16.1FF CRS=10FF CGSO=300PF CGDO=300PF
```

```
VII 9 0 0V AC
VI2 10 0 0V
.AC DEC 20 10MEG 2GIG
.PLOT AC IDB(VOUT15)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
***** OPERATING POINT INFORMATION      THON= 27.000 TEMP= 27.000
```

```
+0:1      = 3.000E+00 0:2      = -3.000E+00 0:3      = 1.145E+00
+0:8      = 1.516E+00 0:9      = 0.          0:10     = 0.
+0:11     = -4.457E-01 0:12     = -1.722E+00 0:15     = 0.
+0:16     = 0.          0:17     = -1.723E+00 0:18     = -1.723E+00
```

***** MOSFETS

KLAMENT	0:M11	0:M1	0:M2	0:M3	0:M4	0:M9
MODEL	0:PMOS	0:PMOS	0:PMOS	0:NMOS	0:NMOS	0:NMOS2
ID	-2.000E-04	-1.000E-04	-1.000E-04	1.000E-04	1.000E-04	2.000E-04
IRS	0.	0.	0.	-1.277E-14	-1.277E-14	0.
IRD	1.484E-14	3.239E-14	3.239E-14	-3.000E-14	-3.000E-14	-1.277E-14
VGS	-1.854E+00	-1.516E+00	-1.516E+00	1.277E+00	1.277E+00	1.277E+00
VDS	-1.483E+00	-3.239E+00	-3.239E+00	1.723E+00	1.723E+00	1.277E+00
VBS	0.	0.	0.	-1.277E+00	-1.277E+00	0.
VTH	-7.000E-01	-7.000E-01	-7.000E-01	7.000E-01	7.000E-01	7.000E-01
VDSAT	-1.154E+00	-8.165E-01	-8.165E-01	5.774E-01	5.774E-01	5.773E-01
BETA	3.000E-04	3.000E-04	3.000E-04	6.000E-04	6.000E-04	1.200E-03
GAM EFF	0.	0.	0.	0.	0.	0.
GM	3.464E-04	2.449E-04	2.449E-04	3.464E-04	3.464E-04	6.928E-04
GDS	0.	0.	0.	0.	0.	0.
GMB	0.	0.	0.	0.	0.	0.
CITOT	1.259E-14	1.029E-14	1.029E-14	1.046E-14	1.046E-14	2.596E-14
CGOT	2.643E-14	2.668E-14	2.668E-14	2.689E-14	2.689E-14	5.374E-14
CSOT	3.302E-14	3.302E-14	3.302E-14	2.922E-14	2.922E-14	6.604E-14
CBOT	1.988E-14	1.770E-14	1.770E-14	1.439E-14	1.439E-14	4.146E-14
CGS	2.302E-14	2.302E-14	2.302E-14	2.302E-14	2.302E-14	4.604E-14
CGD	3.059E-15	1.330E-15	1.330E-15	3.069E-15	3.069E-15	6.102E-15

ELEMENT	0:M10
MODEL	0:NMOS2
ID	2.000E-04
IRS	0.
IED	-1.277E-14
VGS	1.277E+00
VDS	1.277E+00
VBS	0.
VTH	7.000E-01
VDSAT	5.773E-01
BETA	1.200E-03
GAM EFP	0.
GM	6.928E-04
GDS	0.
GMB	0.
CDTOT	2.596E-14
CGTOT	5.374E-14
CBTOT	6.604E-14
CGS	4.146E-14
CGD	4.604E-14
CGO	6.102E-15

***** AC ANALYSIS THOM= 27.000 TEMP= 27.000

FXD	IDB (VOUT15)				
(A)	-8.600E+01	-8.400E+01	-8.200E+01	-8.000E+01	-7.800E+01
1.000E+07	-7.82E+01	+	+	+	+
1.122E+07	-7.82E+01	+	+	+	+
1.258E+07	-7.82E+01	+	+	+	+
1.412E+07	-7.82E+01	+	+	+	+
1.584E+07	-7.82E+01	+	+	+	+
1.778E+07	-7.82E+01	+	+	+	+
1.995E+07	-7.82E+01	+	+	+	+
2.238E+07	-7.82E+01	+	+	+	+
2.511E+07	-7.82E+01	+	+	+	+
2.818E+07	-7.82E+01	+	+	+	+
3.162E+07	-7.82E+01	+	+	+	+
3.548E+07	-7.82E+01	+	+	+	+
3.981E+07	-7.82E+01	+	+	+	+
4.466E+07	-7.82E+01	+	+	+	+
5.011E+07	-7.82E+01	+	+	+	+
5.623E+07	-7.82E+01	+	+	+	+
6.309E+07	-7.82E+01	+	+	+	+
7.079E+07	-7.82E+01	+	+	+	+
7.943E+07	-7.82E+01	+	+	+	+
8.912E+07	-7.82E+01	+	+	+	+
9.999E+07	-7.82E+01	+	+	+	+
1.122E+08	-7.82E+01	+	+	+	+
1.258E+08	-7.83E+01	+	+	+	+
1.412E+08	-7.83E+01	+	+	+	+
1.584E+08	-7.83E+01	+	+	+	+
1.778E+08	-7.83E+01	+	+	+	+
1.995E+08	-7.83E+01	+	+	+	+
2.238E+08	-7.84E+01	+	+	+	+
2.511E+08	-7.94E+01	+	+	+	+
2.818E+08	-7.85E+01	+	+	+	+
3.162E+08	-7.86E+01	+	+	+	+
3.548E+08	-7.86E+01	+	+	+	+
3.981E+08	-7.88E+01	+	+	+	+
4.466E+08	-7.89E+01	+	+	+	+
5.011E+08	-7.90E+01	+	+	+	+
5.623E+08	-7.92E+01	+	+	+	+
6.309E+08	-7.94E+01	+	+	+	+
7.079E+08	-7.97E+01	+	+	+	+
7.943E+08	-8.00E+01	+	+	+	+
8.912E+08	-8.04E+01	+	+	+	+
9.999E+08	-8.08E+01	+	+	+	+
1.122E+09	-8.12E+01	+	+	+	+
1.258E+09	-8.17E+01	+	+	+	+
1.412E+09	-8.22E+01	+	+	+	+
1.584E+09	-8.28E+01	+	+	+	+
1.778E+09	-8.34E+01	+	+	+	+
1.995E+09	-8.40E+01	+	+	+	+
2.238E+09	-8.46E+01	+	+	+	+

BANDWIDTH = 1.12 GIGAHERTZ

FOLDED CASCODE

```
VDD 1 0 3V
VSS 2 0 -3V
M1 8 3 1 1 PMOS W=10U L=1U
V3 3 0 1.1453V
M1 7 9 8 8 PMOS W=10U L=1U
M2 18 10 8 8 PMOS W=10U L=1U
M3 15 11 17 2 NMOS W=10U L=1U
M4 16 11 18 2 NMOS W=10U L=1U
M5 14 13 1 1 PMOS W=10U L=1U
M6 13 13 1 1 PMOS W=10U L=1U
M7 16 15 14 14 PMOS W=10U L=1U
M8 15 15 13 13 PMOS W=10U L=1U
V11 11 0 -0.44565V
M9 18 12 2 2 NMOS2 W=20U L=1U
M10 17 12 2 2 NMOS2 W=20U L=1U
V12 12 0 -1.72265V
CL 16 0 1PF
```

```

.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0
+ TOX=11.5NM CBD=16.1FF CBS=10FF CGSO=300PF CGDO=300PF
.MODEL PMOS2 NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0
+ TOX=11.5NM CBD=32FF CBS=20FF CGSO=300PF CGDO=300PF
.MODEL PMOS PMOS KP=30U VTO=-0.7 LAMBDA=0 LD=0 GAMMA=0
+ TOX=11.5NM CBD=16.1FF CBS=10FF CGSO=300PF CGDO=300PF

```

```

V11 9 0 0V AC
V12 10 0 0V
.AC DEC 40 10MEG 100MEG
.TF V(16) V11
.PLOT AC V(16)
.PLOT AC VP(16)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

```

+0:1      = 3.000E+00 0:2      = -3.000E+00 0:3      = 1.145E+00
+0:8      = 1.516E+00 0:9      = 0.          0:10     = 0.
+0:11     = -4.457E-01 0:12     = -1.722E+00 0:13     = 1.483E+00

```

+0:14 = 1.483E+00 0:15 = -3.299E-02 0:16 = -3.299E-02
 +0:17 = -1.723E+00 0:18 = -1.723E+00

**** MOSFETS

ELEMENT	0:M11	0:M1	0:M2	0:M3	0:M4	0:M5
MODEL	0:PMOS	0:PMOS	0:PMOS	0:NMOS	0:NMOS	0:PMOS
ID	-2.000E-04	-1.000E-04	-1.000E-04	1.000E-04	1.000E-04	-1.000E-04
IBS	0.	0.	0.	-1.277E-14	-1.277E-14	0.
IBD	1.484E-14	3.239E-14	3.239E-14	-2.967E-14	-2.967E-14	1.516E-14
VGS	-1.854E+00	-1.516E+00	-1.516E+00	1.277E+00	1.277E+00	-1.516E+00
VDS	-1.483E+00	-3.239E+00	-3.239E+00	1.690E+00	1.690E+00	-1.516E+00
VBS	0.	0.	0.	-1.277E+00	-1.277E+00	0.
VTH	-7.000E-01	-7.000E-01	-7.000E-01	7.000E-01	7.000E-01	-7.000E-01
VDSAT	-1.154E+00	-8.165E-01	-8.165E-01	5.774E-01	5.774E-01	-8.165E-01
BETA	3.000E-04	3.000E-04	3.000E-04	6.000E-04	6.000E-04	3.000E-04
GAM KFF	0.	0.	0.	0.	0.	0.
GM	3.464E-04	2.449E-04	2.449E-04	3.464E-04	3.464E-04	2.449E-04
GDS	0.	0.	0.	0.	0.	0.
GMB	0.	0.	0.	0.	0.	0.
CUTOT	1.259E-14	1.029E-14	1.029E-14	1.049E-14	1.049E-14	1.252E-14
CGTOT	2.643E-14	2.668E-14	2.668E-14	2.689E-14	2.689E-14	2.661E-14
CSTOT	3.302E-14	3.302E-14	3.302E-14	2.922E-14	2.922E-14	3.302E-14
CBTOT	1.988E-14	1.770E-14	1.770E-14	1.443E-14	1.443E-14	1.999E-14
CGS	2.302E-14	2.302E-14	2.302E-14	2.302E-14	2.302E-14	2.302E-14
CGD	3.059E-15	3.130E-15	3.130E-15	3.068E-15	3.068E-15	3.061E-15

ELEMENT	0:M6	0:M7	0:M8	0:M9	0:M10
MODEL	0:PMOS	0:PMOS	0:PMOS	0:NMOS2	0:NMOS2
ID	-1.000E-04	-1.000E-04	-1.000E-04	2.000E-04	2.000E-04
IBS	0.	0.	0.	0.	0.
IBD	1.516E-14	1.516E-14	1.516E-14	-1.277E-14	-1.277E-14
VGS	-1.516E+00	-1.516E+00	-1.516E+00	1.277E+00	1.277E+00
VDS	-1.516E+00	-1.516E+00	-1.516E+00	1.277E+00	1.277E+00
VBS	0.	0.	0.	0.	0.
VTH	-7.000E-01	-7.000E-01	-7.000E-01	7.000E-01	7.000E-01
VDSAT	-8.165E-01	-8.165E-01	-8.165E-01	5.773E-01	5.773E-01
BETA	3.000E-04	3.000E-04	3.000E-04	1.200E-03	1.200E-03
GAM KFF	0.	0.	0.	0.	0.
GM	2.449E-04	2.449E-04	2.449E-04	6.928E-04	6.928E-04
GDS	0.	0.	0.	0.	0.
GMB	0.	0.	0.	0.	0.
CUTOT	1.252E-14	1.252E-14	1.252E-14	2.596E-14	2.596E-14
CGTOT	2.661E-14	2.661E-14	2.661E-14	5.374E-14	5.374E-14
CSTOT	3.302E-14	3.302E-14	3.302E-14	6.604E-14	6.604E-14
CBTOT	1.999E-14	1.999E-14	1.999E-14	4.146E-14	4.146E-14
CGS	2.302E-14	2.302E-14	2.302E-14	4.604E-14	4.604E-14
CGD	3.061E-15	3.061E-15	3.061E-15	6.102E-15	6.102E-15

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(16)/V(1) = 2.425E+08
 INPUT RESISTANCE AT V(1) = 9.999E+19
 OUTPUT RESISTANCE AT V(16) = 9.901E+11
 ***** AC ANALYSIS THOM= 27.000 TEMP= 27.000

FREQ	V(16)
1.000E+07	3.83E+00
1.059E+07	3.61E+00
1.122E+07	3.42E+00
1.188E+07	3.22E+00
1.258E+07	3.04E+00
1.333E+07	2.87E+00
1.412E+07	2.71E+00
1.496E+07	2.56E+00
1.584E+07	2.41E+00
1.678E+07	2.28E+00
1.778E+07	2.15E+00
1.883E+07	2.03E+00
1.995E+07	1.91E+00
2.113E+07	1.81E+00
2.238E+07	1.71E+00
2.371E+07	1.61E+00
2.511E+07	1.52E+00
2.660E+07	1.43E+00
2.818E+07	1.35E+00
2.985E+07	1.28E+00
3.162E+07	1.20E+00
3.349E+07	1.14E+00
3.548E+07	1.07E+00
3.758E+07	1.01E+00
3.981E+07	9.57E-01
4.217E+07	9.03E-01
4.466E+07	8.52E-01
4.731E+07	8.04E-01
5.011E+07	7.58E-01
5.308E+07	7.15E-01
5.623E+07	6.74E-01
5.956E+07	6.35E-01
6.309E+07	5.99E-01
6.683E+07	5.64E-01
7.079E+07	5.32E-01
7.498E+07	5.01E-01
7.943E+07	4.72E-01
8.414E+07	4.44E-01
8.912E+07	4.18E-01
9.440E+07	3.93E-01
1.000E+08	3.70E-01

FREQ	VP(16)	-1.050E+02	-1.000E+02	-9.500E+01	-9.000E+01
1.000E+07	-9.16E+01	+	+	+	+
1.059E+07	-9.17E+01	+	+	+	+
1.122E+07	-9.18E+01	+	+	+	+
1.188E+07	-9.19E+01	+	+	+	+
1.258E+07	-9.21E+01	+	+	+	+
1.333E+07	-9.22E+01	+	+	+	+
1.412E+07	-9.23E+01	+	+	+	+
1.496E+07	-9.24E+01	+	+	+	+
1.584E+07	-9.26E+01	+	+	+	+
1.678E+07	-9.27E+01	+	+	+	+
1.778E+07	-9.29E+01	+	+	+	+
1.883E+07	-9.31E+01	+	+	+	+
1.995E+07	-9.33E+01	+	+	+	+
2.113E+07	-9.35E+01	+	+	+	+
2.238E+07	-9.37E+01	+	+	+	+
2.371E+07	-9.39E+01	+	+	+	+
2.511E+07	-9.41E+01	+	+	+	+
2.660E+07	-9.44E+01	+	+	+	+
2.818E+07	-9.46E+01	+	+	+	+
2.985E+07	-9.49E+01	+	+	+	+
3.162E+07	-9.52E+01	+	+	+	+
3.349E+07	-9.55E+01	+	+	+	+
3.548E+07	-9.58E+01	+	+	+	+
3.758E+07	-9.62E+01	+	+	+	+
3.981E+07	-9.66E+01	+	+	+	+
4.217E+07	-9.70E+01	+	+	+	+
4.466E+07	-9.74E+01	+	+	+	+
4.731E+07	-9.78E+01	+	+	+	+
5.011E+07	-9.83E+01	+	+	+	+
5.308E+07	-9.87E+01	+	+	+	+
5.623E+07	-9.93E+01	+	+	+	+
5.956E+07	-9.98E+01	+	+	+	+
6.309E+07	-1.00E+02	+	+	+	+
6.683E+07	-1.01E+02	+	+	+	+
7.079E+07	-1.01E+02	+	+	+	+
7.498E+07	-1.02E+02	+	+	+	+
7.943E+07	-1.03E+02	+	+	+	+
8.414E+07	-1.03E+02	+	+	+	+
8.912E+07	-1.04E+02	+	+	+	+
9.440E+07	-1.05E+02	+	+	+	+
1.000E+08	-1.06E+02	+	+	+	+

UNITY GAIN FREQUENCY = 37.58 MEGAHERTZ
 PHASE = -96.2 DEGREES @ 37.58 MEGAHERTZ

FOLDED CASCODE

* TAKE AWAY ALL CAPACITANCES CONTRIBUTING TO
 * THE NON-DOMINANT POLE

VDD 1 0 3V
 VSS 2 0 -3V
 M11 8 3 1 1 PMOS W=10U L=1U
 V3 3 0 1.1453V
 M1 17 9 8 8 P_NOCAP W=10U L=1U
 M2 18 10 8 8 P_NOCAP W=10U L=1U
 M3 15 11 17 2 N_NOCAP W=10U L=1U
 M4 16 11 18 2 N_NOCAP W=10U L=1U
 M5 14 13 1 1 PMOS W=10U L=1U
 M6 13 13 1 1 PMOS W=10U L=1U
 M7 16 15 14 14 PMOS W=10U L=1U
 M8 15 15 13 13 PMOS W=10U L=1U
 V11 11 0 -0.44565V
 M9 18 12 2 2 N_NOCAP W=20U L=1U
 M10 17 12 2 2 N_NOCAP W=20U L=1U
 V12 12 0 -1.72265V
 CL 16 0 1PF
 .MODEL N_NOCAP NMOS KP=60U VTO=0.7 TOX=10M
 .MODEL P_NOCAP PMOS KP=30U VTO=-0.7 TOX=10M
 .MODEL NMOS NMOS KP=60U VTO=0.7
 + TOX=11.5NM CBD=16.1FF CBS=10FF CGSO=300PF CGDO=300PF
 .MODEL PMOS PMOS KP=30U VTO=-0.7
 + TOX=11.5NM CBD=16.1FF CBS=10FF CGSO=300PF CGDO=300PF
 V11 9 0 0V AC
 V12 10 0 0V
 .AC DEC 40 10MEG 100MEG
 .TF V(16) V11
 .PLOT AC V(16)
 .PLOT AC VP(16)
 .OPTIONS NOPAGE NOMOD
 .WIDTH OUT=80
 .OPTIONS SPICE
 .OP
 .END

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

+0:1	= 3.000E+00 0:2	= -3.000E+00 0:3	= 1.145E+00
+0:8	= 1.516E+00 0:9	= 0.	0:10
+0:11	= -4.457E-01 0:12	= -1.722E+00 0:13	= 1.483E+00
+0:14	= 1.483E+00 0:15	= -3.299E-02 0:16	= -3.299E-02
+0:17	= -1.723E+00 0:18	= -1.723E+00	

**** MOSFETS

7-62

ELEMENT	0:M11	0:M1	0:M2	0:M3	0:M4	0:M5	FREQ	VP(16)						
MODEL	0:PMOS	0:P_NOCAP	0:P_NOCAP	0:N_NOCAP	0:N_NOCAP	0:PMOS	(A)	-9.800E+01	-9.800E+01	-9.400E+01	-9.400E+01	-9.200E+01	-9.000E+01	
ID	-2.000E-04	-1.000E-04	-1.000E-04	1.000E-04	1.000E-04	-1.000E-04	1.000E+07	-9.07E+01	+	+	+	+	+	+
IBS	0.	0.	0.	-1.277E-14	-1.277E-14	0.	1.059E+07	-9.08E+01	+	+	+	+	+	+
IBD	1.484E-14	3.239E-14	3.239E-14	-2.967E-14	-2.967E-14	1.516E-14	1.122E+07	-9.08E+01	+	+	+	+	+	+
VGS	-1.854E+00	-1.516E+00	-1.516E+00	1.277E+00	1.277E+00	-1.516E+00	1.188E+07	-9.09E+01	+	+	+	+	+	+
VDS	-1.483E+00	-3.239E+00	-3.239E+00	1.690E+00	1.690E+00	-1.516E+00	1.258E+07	-9.09E+01	+	+	+	+	+	+
VBS	0.	0.	0.	-1.277E+00	-1.277E+00	0.	1.333E+07	-9.10E+01	+	+	+	+	+	+
VTH	-7.000E-01	-7.000E-01	-7.000E-01	7.000E-01	7.000E-01	-7.000E-01	1.412E+07	-9.11E+01	+	+	+	+	+	+
VDSAT	-1.154E+00	-8.165E-01	-8.165E-01	5.774E-01	5.774E-01	-8.165E-01	1.496E+07	-9.11E+01	+	+	+	+	+	+
BETA	3.000E-04	3.000E-04	3.000E-04	6.000E-04	6.000E-04	3.000E-04	1.584E+07	-9.12E+01	+	+	+	+	+	+
GAIN EFF	0.	0.	0.	0.	0.	0.	1.678E+07	-9.13E+01	+	+	+	+	+	+
GM	3.464E-04	2.449E-04	2.449E-04	3.464E-04	3.464E-04	2.449E-04	1.778E+07	-9.14E+01	+	+	+	+	+	+
GDS	0.	0.	0.	0.	0.	0.	1.883E+07	-9.14E+01	+	+	+	+	+	+
GMB	0.	0.	0.	0.	0.	0.	1.995E+07	-9.15E+01	+	+	+	+	+	+
CDTOT	1.259E-14	1.492E-22	1.492E-22	7.781E-23	7.781E-23	1.252E-14	2.113E+07	-9.16E+01	+	+	+	+	+	+
CGTOT	2.643E-14	2.378E-20	2.378E-20	2.402E-20	2.402E-20	2.661E-14	2.238E+07	-9.17E+01	+	+	+	+	+	+
CSTOT	3.302E-14	2.302E-20	2.302E-20	2.302E-20	2.302E-20	3.302E-14	2.371E+07	-9.18E+01	+	+	+	+	+	+
CBTOT	1.988E-14	6.126E-22	6.126E-22	9.206E-22	9.206E-22	1.999E-14	2.511E+07	-9.19E+01	+	+	+	+	+	+
CGS	2.302E-14	2.302E-20	2.302E-20	2.302E-20	2.302E-20	2.302E-14	2.660E+07	-9.20E+01	+	+	+	+	+	+
CGD	3.059E-15	1.492E-22	1.492E-22	7.781E-23	7.781E-23	3.061E-15	2.818E+07	-9.22E+01	+	+	+	+	+	+

ELEMENT	0:M6	0:M7	0:M8	0:M9	0:M10
MODEL	0:PMOS	0:PMOS	0:PMOS	0:N_NOCAP	0:N_NOCAP
ID	-1.000E-04	-1.000E-04	-1.000E-04	2.000E-04	2.000E-04
IBS	0.	0.	0.	0.	0.
IBD	1.516E-14	1.516E-14	1.516E-14	-1.277E-14	-1.277E-14
VGS	-1.516E+00	-1.516E+00	-1.516E+00	1.277E+00	1.277E+00
VDS	-1.516E+00	-1.516E+00	-1.516E+00	1.277E+00	1.277E+00
VBS	0.	0.	0.	0.	0.
VTH	-7.000E-01	-7.000E-01	-7.000E-01	7.000E-01	7.000E-01
VDSAT	-8.165E-01	-8.165E-01	-8.165E-01	5.773E-01	5.773E-01
BETA	3.000E-04	3.000E-04	3.000E-04	1.200E-03	1.200E-03
GAIN EFF	0.	0.	0.	0.	0.
GM	2.449E-04	2.449E-04	2.449E-04	6.928E-04	6.928E-04
GDS	0.	0.	0.	0.	0.
GMB	0.	0.	0.	0.	0.
CDTOT	1.252E-14	1.252E-14	1.252E-14	1.176E-22	1.176E-22
CGTOT	2.661E-14	2.661E-14	2.661E-14	4.800E-20	4.800E-20
CSTOT	3.302E-14	3.302E-14	3.302E-14	4.604E-20	4.604E-20
CBTOT	1.999E-14	1.999E-14	1.999E-14	1.841E-21	1.841E-21
CGS	2.302E-14	2.302E-14	2.302E-14	4.604E-20	4.604E-20
CGD	3.061E-15	3.061E-15	3.061E-15	1.176E-22	1.176E-22

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

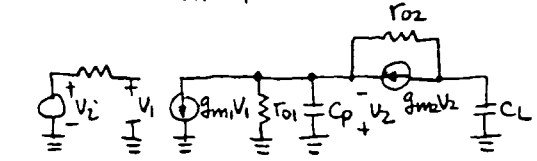
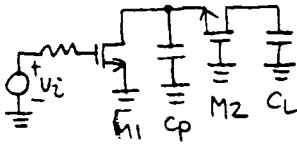
V(16)/V11 = 2.425E+08
 INPUT RESISTANCE AT V11 = 9.999E+19
 OUTPUT RESISTANCE AT V(16) = 9.901E+11

UNITY GAIN FREQUENCY = 37.58 MEGAHERTZ
 PHASE = -92.9 DEGREES @ 37.58 MEGAHERTZ

***** AC ANALYSIS TNOM= 27.000 TEMP= 27.000

FREQ	V(16)				
(A)	0.	1.000E+00	2.000E+00	3.000E+00	4.000E+00
1.000E+07	3.87E+00	+	+	+	+
1.059E+07	3.65E+00	+	+	+	+
1.122E+07	3.45E+00	+	+	+	+
1.188E+07	3.25E+00	+	+	+	+
1.258E+07	3.07E+00	+	+	+	+
1.333E+07	2.92E+00	+	+	+	+
1.412E+07	2.74E+00	+	+	+	+
1.496E+07	2.58E+00	+	+	+	+
1.584E+07	2.44E+00	+	+	+	+
1.678E+07	2.30E+00	+	+	+	+
1.778E+07	2.17E+00	+	+	+	+
1.883E+07	2.05E+00	+	+	+	+
1.995E+07	1.94E+00	+	+	+	+
2.113E+07	1.83E+00	+	+	+	+
2.238E+07	1.72E+00	+	+	+	+
2.371E+07	1.63E+00	+	+	+	+
2.511E+07	1.54E+00	+	+	+	+
2.660E+07	1.45E+00	+	+	+	+
2.818E+07	1.37E+00	+	+	+	+
2.985E+07	1.29E+00	+	+	+	+
3.162E+07	1.22E+00	+	+	+	+
3.349E+07	1.15E+00	+	+	+	+
3.548E+07	1.08E+00	+	+	+	+
3.758E+07	1.02E+00	+	+	+	+
3.991E+07	9.75E+01	+	+	+	+
4.217E+07	9.16E+01	+	+	+	+
4.466E+07	8.54E+01	+	+	+	+
4.731E+07	8.15E+01	+	+	+	+
5.011E+07	7.69E+01	+	+	+	+
5.308E+07	7.26E+01	+	+	+	+
5.623E+07	6.85E+01	+	+	+	+
5.956E+07	6.46E+01	+	+	+	+
6.309E+07	6.09E+01	+	+	+	+
6.683E+07	5.75E+01	+	+	+	+
7.079E+07	5.42E+01	+	+	+	+
7.498E+07	5.11E+01	+	+	+	+
7.943E+07	4.82E+01	+	+	+	+
8.414E+07	4.54E+01	+	+	+	+
8.912E+07	4.29E+01	+	+	+	+
9.440E+07	4.03E+01	+	+	+	+
1.000E+08	3.82E+01	+	+	+	+

7.43



$$g_{m2} = \sqrt{2k' \frac{W}{L} I_D} = \sqrt{2 \times 180 \times 10^{-6} \times \frac{20}{0.5} \times 100 \times 10^{-6}}$$

$$= 1.2 \times 10^{-3} \text{ A/V}$$

$$r_{o1} = \frac{1}{\lambda I_D} = \frac{1}{0.04 \times 100 \times 10^{-6}} = 2.5 \times 10^5 \Omega = r_{o2}$$

(a) With C_L open

$$C_p r_{o1} = 0.2 \times 10^{-12} \times 2.5 \times 10^5 = 5 \times 10^{-8} \text{ s}$$

With C_p open

$$C_L (r_{o1} + r_{o2} + g_{m2} r_{o1} r_{o2})$$

$$= 2 \times 10^{-12} (2.5 \times 10^5 + 2.5 \times 10^5 + 1.2 \times 10^{-3} \times 2.5 \times 10^5 \times 2.5 \times 10^5)$$

$$= 1.5 \times 10^{-4} \text{ s}$$

$$P_1 = -\frac{1}{5 \times 10^{-8} + 1.5 \times 10^{-4}} = -6.6 \times 10^3 \text{ rad/s}$$

(b) With C_p short

$$C_L r_{o2} = 2 \times 10^{-12} \times 2.5 \times 10^5 = 5 \times 10^{-7} \text{ s}$$

With C_L short

$$C_p (g_{m2} \parallel r_{o1} \parallel r_{o2}) \approx \frac{C_p}{g_{m2}} = \frac{0.2 \times 10^{-12}}{1.2 \times 10^{-3}}$$

$$= 1.7 \times 10^{-10} \text{ s}$$

$$P_2 = -\left(\frac{1}{5 \times 10^{-7}} + \frac{1}{1.7 \times 10^{-10}}\right) \approx -6 \times 10^9 \text{ rad/s}$$

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```
MOS CASCODE STAGE
VI 1 0 DC 1.165 AC 1
VB1 4 0 1.67
VB2 5 0 5
IB 5 3 100V
CP 2 0 0.2P
CL 3 0 2P
M1 2 1 0 0 CHMOSN W=20U L=0.5U
M2 3 4 2 2 CHMOSN W=20U L=0.5U
.MODEL CHMOSN NMOS VTO=1 KP=180U LAMBDA=0.04
.OPTIONS NOMOD
.AC DEC 5 100 100G
.PLOT AC VM(3)
.WIDTH OUT=80
.OPTIONS SPICE
.END
```

```
***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000
+0:1 = 1.165E+00 0:2 = 5.076E-01 0:3 = 1.838E+00
+0:4 = 1.670E+00 0:5 = 5.000E+00
```

**** MOSFETS

```
SUBCKT
ELEMENT 0:M1 0:M2
MODEL 0:CHMOSN 0:CHMOSN
ID 1.000E-04 1.000E-04
IBS 0. 0.
IBD -5.076E-15 -1.331E-14
VGS 1.165E+00 1.162E+00
VDS 5.076E-01 1.331E+00
VBS 0. 0.
VTH 1.000E+00 1.000E+00
VDSAT 1.650E-01 1.624E-01
BETA 7.346E-03 7.583E-03
GAM EFF 0. 0.
GM 1.212E-03 1.232E-03
GDS 3.920E-06 3.798E-06
GMB 0. 0.
CMTOT 0. 0.
CGTOT 0. 0.
CBTOT 0. 0.
CGS 0. 0.
CGD 0. 0.
```

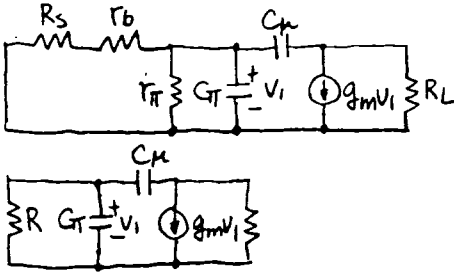
***** AC ANALYSIS

THOM= 27.000 TEMP= 27.000

FA	FLRQ	VM(3)	1.000E-05	1.000E+00	1.000E+05	1.000E+10
1.000E+02	1.00E+05	1.00E+05	1.00E+05	1.00E+05	1.00E+05	1.00E+05
1.584E+02	9.92E+04	9.92E+04	9.92E+04	9.92E+04	9.92E+04	9.92E+04
2.511E+02	9.72E+04	9.72E+04	9.72E+04	9.72E+04	9.72E+04	9.72E+04
3.981E+02	9.28E+04	9.28E+04	9.28E+04	9.28E+04	9.28E+04	9.28E+04
6.309E+02	8.39E+04	8.39E+04	8.39E+04	8.39E+04	8.39E+04	8.39E+04
1.000E+03	6.94E+04	6.94E+04	6.94E+04	6.94E+04	6.94E+04	6.94E+04
1.584E+03	5.19E+04	5.19E+04	5.19E+04	5.19E+04	5.19E+04	5.19E+04
2.511E+03	3.57E+04	3.57E+04	3.57E+04	3.57E+04	3.57E+04	3.57E+04
3.981E+03	2.34E+04	2.34E+04	2.34E+04	2.34E+04	2.34E+04	2.34E+04
6.309E+03	1.50E+04	1.50E+04	1.50E+04	1.50E+04	1.50E+04	1.50E+04
1.000E+04	9.56E+03	9.56E+03	9.56E+03	9.56E+03	9.56E+03	9.56E+03
1.584E+04	6.05E+03	6.05E+03	6.05E+03	6.05E+03	6.05E+03	6.05E+03
2.511E+04	3.82E+03	3.82E+03	3.82E+03	3.82E+03	3.82E+03	3.82E+03
3.981E+04	2.41E+03	2.41E+03	2.41E+03	2.41E+03	2.41E+03	2.41E+03
6.309E+04	1.52E+03	1.52E+03	1.52E+03	1.52E+03	1.52E+03	1.52E+03
1.000E+05	9.61E+02	9.61E+02	9.61E+02	9.61E+02	9.61E+02	9.61E+02
1.584E+05	6.06E+02	6.06E+02	6.06E+02	6.06E+02	6.06E+02	6.06E+02
2.511E+05	3.82E+02	3.82E+02	3.82E+02	3.82E+02	3.82E+02	3.82E+02
3.981E+05	2.41E+02	2.41E+02	2.41E+02	2.41E+02	2.41E+02	2.41E+02
6.309E+05	1.52E+02	1.52E+02	1.52E+02	1.52E+02	1.52E+02	1.52E+02
1.000E+06	9.61E+01	9.61E+01	9.61E+01	9.61E+01	9.61E+01	9.61E+01
1.584E+06	6.06E+01	6.06E+01	6.06E+01	6.06E+01	6.06E+01	6.06E+01
2.511E+06	3.82E+01	3.82E+01	3.82E+01	3.82E+01	3.82E+01	3.82E+01
3.981E+06	2.41E+01	2.41E+01	2.41E+01	2.41E+01	2.41E+01	2.41E+01
6.309E+06	1.52E+01	1.52E+01	1.52E+01	1.52E+01	1.52E+01	1.52E+01
1.000E+07	9.61E+00	9.61E+00	9.61E+00	9.61E+00	9.61E+00	9.61E+00
1.584E+07	6.06E+00	6.06E+00	6.06E+00	6.06E+00	6.06E+00	6.06E+00
2.511E+07	3.82E+00	3.82E+00	3.82E+00	3.82E+00	3.82E+00	3.82E+00
3.981E+07	2.41E+00	2.41E+00	2.41E+00	2.41E+00	2.41E+00	2.41E+00
6.309E+07	1.52E+00	1.52E+00	1.52E+00	1.52E+00	1.52E+00	1.52E+00
1.000E+08	9.56E+01	9.56E+01	9.56E+01	9.56E+01	9.56E+01	9.56E+01
1.584E+08	5.99E+01	5.99E+01	5.99E+01	5.99E+01	5.99E+01	5.99E+01
2.511E+08	3.71E+01	3.71E+01	3.71E+01	3.71E+01	3.71E+01	3.71E+01
3.981E+08	2.24E+01	2.24E+01	2.24E+01	2.24E+01	2.24E+01	2.24E+01
6.309E+08	1.28E+01	1.28E+01	1.28E+01	1.28E+01	1.28E+01	1.28E+01
1.000E+09	6.75E+00	6.75E+00	6.75E+00	6.75E+00	6.75E+00	6.75E+00
1.584E+09	3.20E+00	3.20E+00	3.20E+00	3.20E+00	3.20E+00	3.20E+00
2.511E+09	1.40E+00	1.40E+00	1.40E+00	1.40E+00	1.40E+00	1.40E+00
3.981E+09	5.81E-01	5.81E-01	5.81E-01	5.81E-01	5.81E-01	5.81E-01
6.309E+09	2.35E-01	2.35E-01	2.35E-01	2.35E-01	2.35E-01	2.35E-01
1.000E+10	9.44E-02	9.44E-02	9.44E-02	9.44E-02	9.44E-02	9.44E-02
1.584E+10	3.77E-02	3.77E-02	3.77E-02	3.77E-02	3.77E-02	3.77E-02
2.511E+10	1.50E-02	1.50E-02	1.50E-02	1.50E-02	1.50E-02	1.50E-02
3.981E+10	5.98E-03	5.98E-03	5.98E-03	5.98E-03	5.98E-03	5.98E-03
6.309E+10	2.38E-03	2.38E-03	2.38E-03	2.38E-03	2.38E-03	2.38E-03
1.000E+11	9.48E-04	9.48E-04	9.48E-04	9.48E-04	9.48E-04	9.48E-04

7-64

7.44



$$R_s = 5k\Omega, r_b = 300\Omega, r_{\pi} = 10.4k\Omega,$$

$$R_L = 3k\Omega, R = (R_s + r_b) \parallel r_{\pi} = 3.5k\Omega$$

$$g_m = \frac{I_c}{V_T} = \frac{0.5mA}{26mV} = 0.019A/V$$

$$C_{\pi} = 5.8pF, C_e = 0.3pF$$

The dominant pole (open circuit TC)

$$G_{TR} = 5.8 \times 10^{-12} \times 3.5 \times 10^3 = 2 \times 10^{-8}s$$

$$C_e(R + R_L + g_m R R_L)$$

$$= 0.3 \times 10^{-12} (3.5 \times 10^3 + 3 \times 10^3 + 0.019 \times 3.5 \times 10^3 \times 3 \times 10^3)$$

$$= 6.2 \times 10^{-8}s$$

$$P_1 = -\frac{1}{2 \times 10^{-8} + 6.2 \times 10^{-8}} = -1.2 \times 10^7 \text{ rad/s}$$

The nondominant pole (short circuit TC)

$$G_{TR} (R \parallel \frac{1}{g_m} \parallel R_L) = 5.8 \times 10^{-12} (3.5 \times 10^3 \parallel \frac{1}{0.019} \parallel 3 \times 10^3)$$

$$= 3 \times 10^{-10}s$$

$$C_e R_L = 0.3 \times 10^{-12} \times 3 \times 10^3 = 9 \times 10^{-10}s$$

$$P_2 = -\left(\frac{1}{3 \times 10^{-10}} + \frac{1}{9 \times 10^{-10}}\right) = -4.4 \times 10^9 \text{ rad/s}$$

COMMON EMITTER GAIN STAGE

```
VCC 1 0 5V
RL 1 2 3K
Q1 2 3 0 NPN
RS 4 3 5K
VI 4 0 0.7696 AC
.PLOT AC VDB(2)
.AC DEC 8 100K 10GIG
.MODEL NPN NPN IS=1E-16A BF=200
+ RB=300 CJC=0.3PF CJS=0 TF=302PS
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

```
***** OPERATING POINT INFORMATION      TNOM= 27.000 TEMP= 27.000
+0:1      = 5.000E+00 0:2      = 3.497E+00 0:3      = 7.571E-01
+0:4      = 7.696E-01
```

**** BIPOLAR JUNCTION TRANSISTORS

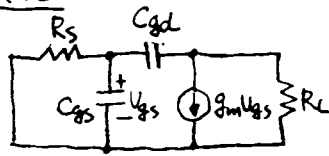
```
ELEMENT 0:Q1
MODEL 0:NPN
IB 2.504E-06
IC 5.009E-04
VBE 7.571E-01
VCE 3.497E+00
VBC -2.740E+00
VS -3.497E+00
POWER 1.754E-03
BETAD 2.000E+02
GM 1.937E-02
RPI 1.032E+04
RX 3.000E+02
RO 2.741E+16
CPI 5.849E-12
CMU 1.806E-13
CBX 0.
CCS 0.
BETAAC 2.000E+02
FT 5.112E+08
```

***** AC ANALYSIS

```
TNOM= 27.000 TEMP= 27.000
FREQ VDB(2)
(A) 1 -1.000E+02 -5.000E+01 0. 5.000E+01 1.000E+02
1.000E+05 3.16E+01 + + + + + A + + +
1.333E+05 3.16E+01 + + + + + A + + +
1.778E+05 3.16E+01 + + + + + A + + +
2.371E+05 3.16E+01 + + + + + A + + +
3.162E+05 3.16E+01 + + + + + A + + +
4.217E+05 3.16E+01 + + + + + A + + +
5.623E+05 3.16E+01 + + + + + A + + +
7.498E+05 3.16E+01 + + + + + A + + +
1.000E+06 3.16E+01 + + + + + A + + +
1.333E+06 3.16E+01 + + + + + A + + +
1.778E+06 3.16E+01 + + + + + A + + +
2.371E+06 2.92E+01 + + + + + A + + +
3.162E+06 2.80E+01 + + + + + A + + +
4.217E+06 2.64E+01 + + + + + A + + +
5.623E+06 2.45E+01 + + + + + A + + +
7.498E+06 2.23E+01 + + + + + A + + +
1.000E+07 2.01E+01 + + + + + A + + +
1.333E+07 1.77E+01 + + + + + A + + +
1.778E+07 1.53E+01 + + + + + A + + +
2.371E+07 1.28E+01 + + + + + A + + +
3.162E+07 1.03E+01 + + + + + A + + +
4.217E+07 7.89E+00 + + + + + A + + +
5.623E+07 5.39E+00 + + + + + A + + +
7.498E+07 2.88E+00 + + + + + A + + +
1.000E+08 3.56E+01 + + + + + A + + +
1.333E+08 -2.19E+00 + + + + + A + + +
1.778E+08 -4.77E+00 + + + + + A + + +
2.371E+08 -7.41E+00 + + + + + A + + +
3.162E+08 -1.01E+01 + + + + + A + + +
4.217E+08 -1.30E+01 + + + + + A + + +
5.623E+08 -1.62E+01 + + + + + A + + +
7.498E+08 -1.96E+01 + + + + + A + + +
1.000E+09 -2.34E+01 + + + + + A + + +
1.333E+09 -2.75E+01 + + + + + A + + +
1.778E+09 -3.19E+01 + + + + + A + + +
2.371E+09 -3.65E+01 + + + + + A + + +
3.162E+09 -4.12E+01 + + + + + A + + +
4.217E+09 -4.60E+01 + + + + + A + + +
5.623E+09 -5.07E+01 + + + + + A + + +
7.498E+09 -5.54E+01 + + + + + A + + +
1.000E+10 -5.99E+01 + + + + + A + + +
```

7-65

7.45



The dominant pole (open circuit TC)

$$C_{gs}R_s = 89 \times 10^{-15} \times 10 \times 10^3 = 8.9 \times 10^{-10} \text{ s}$$

$$C_{gd}(R_s + R_L + g_m R_s R_L)$$

$$= 14 \times 10^{-15} (10 \times 10^3 + 5 \times 10^3 + 1.9 \times 10^{-3} \times 10 \times 10^3 \times 5 \times 10^3)$$

$$= 1.5 \times 10^{-9} \text{ s}$$

$$P_1 = -\frac{1}{8.9 \times 10^{-10} + 1.5 \times 10^{-9}} = -4.2 \times 10^8 \text{ rad/s}$$

The nondominant pole (short circuit TC)

$$C_{gs}(R_s \parallel \frac{1}{g_m} \parallel R_L)$$

$$= 89 \times 10^{-15} (10 \times 10^3 \parallel \frac{1}{1.9 \times 10^{-3}} \parallel 5 \times 10^3)$$

$$= 4 \times 10^{-11} \text{ s}$$

$$C_{gd}R_L = 14 \times 10^{-15} \times 5 \times 10^3 = 7 \times 10^{-11} \text{ s}$$

$$P_2 = -\left(\frac{1}{4 \times 10^{-11}} + \frac{1}{7 \times 10^{-11}}\right) = -3.9 \times 10^{10} \text{ rad/s}$$

COMMON SOURCE AMPLIFIER

```

VDD 1 0 5
VI 2 0 DC 1.216 AC 1
RS 2 3 10K
RL 1 4 5K
M1 4 3 0 0 CMOSN W=100U L=2U
* COX'=0.7FF/UM**2=BOX/TOX => TOX=500 ANGSTROMS
.MODEL CMOSN NMOS LEVEL=1 LAMBDA=0 VTO=0.7 KP=60U LD=0.2U TOX=500E-10
.OPTIONS NOMOD
.AC DEC 10 10MEG 100G
.PLOT AC VM(4)
.WIDTH OUT=80
.OPTIONS SPICE
.END

```

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

+0:1 = 5.000E+00 0:2 = 1.216E+00 0:3 = 1.216E+00
+0:4 = 2.503E+00

**** MOSFETS

```

ELEMENT 0:M1
MODEL 0:CMOSN
ID 4.992E-04
IBS 0.
IRD -2.504E-14
VGS 1.216E+00
VDS 2.503E+00
VBS 0.
VTH 7.000E-01
VDSAT 5.160E-01
BETA 3.750E-03
GAM EFF 0.
GM 1.935E-03
GDS 0.
GMB 0.
COTOT 1.418E-14
CGTOT 1.050E-13
CSTOT 8.748E-14
CPTOT 3.349E-15
CGS 8.748E-14
CGD 1.418E-14

```

***** AC ANALYSIS

THOM= 27.000 TEMP= 27.000

FREQ	VM(4)	1.000E-03	1.000E-02	1.000E-01	1.000E+00	1.000E+01
1.000E+07	9.56E+00	*	*	*	*	*
1.258E+07	9.49E+00	*	*	*	*	A
1.584E+07	9.39E+00	*	*	*	*	A
1.995E+07	9.24E+00	*	*	*	*	A
2.511E+07	9.01E+00	*	*	*	*	A+
3.162E+07	8.68E+00	*	*	*	*	A+
3.981E+07	8.23E+00	*	*	*	*	A+
5.011E+07	7.64E+00	*	*	*	*	A+
6.309E+07	6.91E+00	*	*	*	*	A+
7.943E+07	6.09E+00	*	*	*	*	A+
1.000E+08	5.24E+00	*	*	*	*	A
1.258E+08	4.41E+00	*	*	*	*	A+
1.584E+08	3.64E+00	*	*	*	*	A+
1.995E+08	2.97E+00	*	*	*	*	A
2.511E+08	2.40E+00	*	*	*	*	A+
3.162E+08	1.93E+00	*	*	*	*	A+
3.981E+08	1.54E+00	*	*	*	*	A+
5.011E+08	1.23E+00	*	*	*	*	A
6.309E+08	9.79E-01	*	*	*	*	A
7.943E+08	7.77E-01	*	*	*	*	A+
1.000E+09	6.15E-01	*	*	*	*	A
1.258E+09	4.86E-01	*	*	*	*	A+
1.584E+09	3.82E-01	*	*	*	*	A+
1.995E+09	2.98E-01	*	*	*	*	A+
2.511E+09	2.31E-01	*	*	*	*	A+
3.162E+09	1.77E-01	*	*	*	*	A+
3.981E+09	1.33E-01	*	*	*	*	A+
5.011E+09	9.87E-02	*	*	*	*	A+
6.309E+09	7.16E-02	*	*	*	*	A+
7.943E+09	5.09E-02	*	*	*	*	A+
1.000E+10	3.58E-02	*	*	*	*	A
1.258E+10	2.50E-02	*	*	*	*	A+
1.584E+10	1.75E-02	*	*	*	*	A+
1.995E+10	1.24E-02	*	*	*	*	A+
2.511E+10	8.96E-03	*	*	*	*	A+
3.162E+10	6.60E-03	*	*	*	*	A+
3.981E+10	4.96E-03	*	*	*	*	A+
5.011E+10	3.78E-03	*	*	*	*	A+
6.309E+10	2.92E-03	*	*	*	*	A+
7.943E+10	2.28E-03	*	*	*	*	A+
1.000E+11	1.79E-03	*	*	*	*	A

7-66

7.46

To calculate the dominant pole, calculate the open circuit time constants

$$C_{in}R = 2 \times 10^{-12} \times 20 \times 10^3 = 4 \times 10^{-9} \text{ s}$$

$$C(R + R_o + \frac{a_v}{R_o} R R_o) = C(R + R_o + a_v R)$$

$$= C[(1 + a_v)R + R_o]$$

$$= 50 \times 10^{-12} [(1 + 1000)20 \times 10^3 + 5 \times 10^3]$$

$$= 1 \times 10^{-3} \text{ s}$$

$$P_1 = -\frac{1}{4 \times 10^{-9} + 1 \times 10^{-3}} = -1 \times 10^3 \text{ rad/s}$$

To calculate the non dominant pole, calculate the short circuit time constants

$$C_{in}(R \parallel \frac{R_o}{a_v} \parallel R_o) = 2 \times 10^{-12} (20 \times 10^3 \parallel \frac{5 \times 10^3}{1000} \parallel 5 \times 10^3)$$

$$= 1 \times 10^{-12} \text{ s}$$

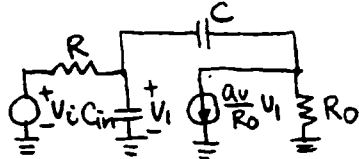
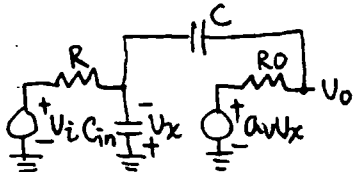
$$C R_o = 50 \times 10^{-12} \times 5 \times 10^3 = 2.5 \times 10^{-7} \text{ s}$$

$$P_2 = -(\frac{1}{1 \times 10^{-12}} + \frac{1}{2.5 \times 10^{-7}}) = -1 \times 10^{12} \text{ rad/s}$$

Note that there is a zero at

$$z = -\frac{a_v/R_o}{C} = -\frac{1000/5 \times 10^3}{50 \times 10^{-12}} = -4 \times 10^9 \text{ rad/s}$$

It is between the two poles and confirmed by SPICE.



```

INTEGRATOR
VI 1 0 AC 1
R 1 2 20K
RO 3 4 5K
CIN 2 0 0.2P
C 2 3 50P
E 4 0 0 2 1000

```

```

.OPTIONS NOMOD
.AC DEC 5 10 1000G
.PLOT AC VM(3)
.WIDTH OUT=80
.OPTIONS SPICE
.END

```

```

***** OPERATING POINT INFORMATION      THOM= 27.000 TEMP= 27.000
+0:1      = 0.      0:2      = 0.      0:3      = 0.
+0:4      = 0.

```

```

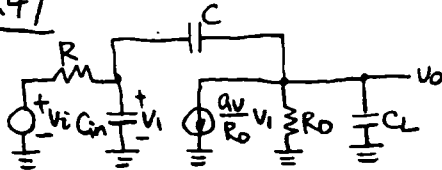
***** AC ANALYSIS      THOM= 27.000 TEMP= 27.000

```

FREQ	VM(3)					
(A)		1.000E-10	1.000E-05	1.000E+00	1.000E+05	1.000E+10
1.000E+01	9.98E+02	+	+	+	+	+
1.584E+01	9.95E+02	+	+	+	+	+
2.511E+01	9.87E+02	+	+	+	+	+
3.981E+01	9.70E+02	+	+	+	+	+
6.309E+01	9.29E+02	+	+	+	+	+
1.000E+02	8.46E+02	+	+	+	+	+
1.584E+02	7.08E+02	+	+	+	+	+
2.511E+02	5.34E+02	+	+	+	+	+
3.981E+02	3.70E+02	+	+	+	+	+
6.309E+02	2.44E+02	+	+	+	+	+
1.000E+03	1.57E+02	+	+	+	+	+
1.584E+03	9.97E+01	+	+	+	+	+
2.511E+03	6.31E+01	+	+	+	+	+
3.981E+03	3.99E+01	+	+	+	+	+
6.309E+03	2.51E+01	+	+	+	+	+
1.000E+04	1.58E+01	+	+	+	+	+
1.584E+04	1.00E+01	+	+	+	+	+
2.511E+04	6.32E+00	+	+	+	+	+
3.981E+04	3.99E+00	+	+	+	+	+
6.309E+04	2.51E+00	+	+	+	+	+
1.000E+05	1.59E+00	+	+	+	+	+
1.584E+05	1.00E+00	+	+	+	+	+
2.511E+05	6.33E-01	+	+	+	+	+
3.981E+05	3.99E-01	+	+	+	+	+
6.309E+05	2.52E-01	+	+	+	+	+
1.000E+06	1.59E-01	+	+	+	+	+
1.584E+06	1.00E-01	+	+	+	+	+
2.511E+06	6.33E-02	+	+	+	+	+
3.981E+06	3.99E-02	+	+	+	+	+
6.309E+06	2.52E-02	+	+	+	+	+
1.000E+07	1.59E-02	+	+	+	+	+
1.584E+07	1.00E-02	+	+	+	+	+
2.511E+07	6.33E-03	+	+	+	+	+
3.981E+07	4.00E-03	+	+	+	+	+
6.309E+07	2.53E-03	+	+	+	+	+
1.000E+08	1.61E-03	+	+	+	+	+
1.584E+08	1.03E-03	+	+	+	+	+
2.511E+08	6.80E-04	+	+	+	+	+
3.981E+08	4.71E-04	+	+	+	+	+
6.309E+08	3.55E-04	+	+	+	+	+
1.000E+09	2.96E-04	+	+	+	+	+
1.584E+09	2.69E-04	+	+	+	+	+
2.511E+09	2.50E-04	+	+	+	+	+
3.981E+09	2.53E-04	+	+	+	+	+
6.309E+09	2.51E-04	+	+	+	+	+
1.000E+10	2.50E-04	+	+	+	+	+
1.584E+10	2.49E-04	+	+	+	+	+
2.511E+10	2.47E-04	+	+	+	+	+
3.981E+10	2.42E-04	+	+	+	+	+
6.309E+10	2.32E-04	+	+	+	+	+
1.000E+11	2.11E-04	+	+	+	+	+
1.584E+11	1.77E-04	+	+	+	+	+
2.511E+11	1.34E-04	+	+	+	+	+
3.981E+11	9.28E-05	+	+	+	+	+
6.309E+11	6.11E-05	+	+	+	+	+
1.000E+12	3.93E-05	+	+	+	+	+

7-67

7.47



The zero value time constants

$$C_{in}R = 0.2 \times 10^{-12} \times 20 \times 10^3 = 4 \times 10^{-9} \text{ s}$$

$$C(R + R_o + \frac{a_v}{R_o} R R_o) = C(R + R_o + a_v R)$$

$$= C[(1 + a_v)R + R_o]$$

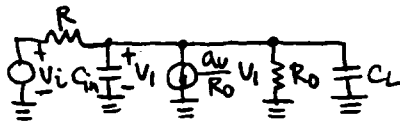
$$= 50 \times 10^{-12} [(1 + 1000)20 \times 10^3 + 5 \times 10^3]$$

$$= 1 \times 10^{-3} \text{ s}$$

$$C_L R_o = 0.5 \times 10^{-12} \times 5 \times 10^3 = 2.5 \times 10^{-9} \text{ s}$$

$$P_1 = -\frac{1}{4 \times 10^{-9} + 1 \times 10^{-3} + 2.5 \times 10^{-9}} = -1 \times 10^3 \text{ rad/s}$$

$1 \times 10^{-3} \text{ s} \gg 4 \times 10^{-9} \text{ s}, 2.5 \times 10^{-9} \text{ s}$. C is shorted.



$$(C_{in} + C)(R \parallel \frac{R_o}{a_v} \parallel R_o)$$

$$\approx (C_{in} + C) \frac{R_o}{a_v}$$

$$= (0.2 + 0.5) \times 10^{-12} \frac{5 \times 10^3}{1000}$$

$$= 3.5 \times 10^{-12} \text{ s}$$

$$P_2 = -\frac{1}{3.5 \times 10^{-12}} = -2.9 \times 10^{11} \text{ rad/s}$$

Note that there is a zero at

$$z = -\frac{a_v/R_o}{C} = -\frac{1000/5 \times 10^3}{50 \times 10^{-12}} = -4 \times 10^9 \text{ rad/s}$$

It is between the two poles and confirmed by SPICE.

INTEGRATOR

```

VI 1 0 AC 1
R 1 2 20K
RO 3 4 5K
CIN 2 0 0.2P
C 2 3 50P
CL 3 0 0.5P
E 4 0 0 2 1000

```

```

.OPTIONS NOMOD
.AC DEC 5 10 100G
.PLOT AC VM(3)
.WIDTH OUT=80
.OPTIONS SPICE
.END

```

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

```

+0:1 = 0. 0:2 = 0. 0:3 = 0.
+0:4 = 0.

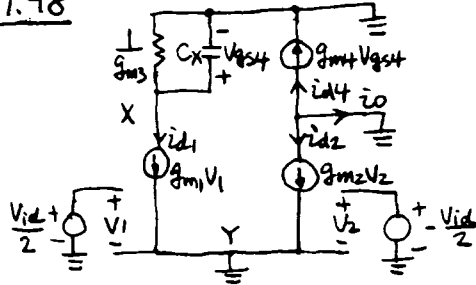
```

***** AC ANALYSIS

THOM= 27.000 TEMP= 27.000

FREQ	VM(3)				
(A)		1.000E-04	1.000E-02	1.000E+00	1.000E+02
1.000E+01	9.98E+02				A
1.584E+01	9.95E+02				A
2.511E+01	9.87E+02				A
3.981E+01	9.70E+02				A
6.309E+01	9.29E+02				A
1.000E+02	8.46E+02				A
1.584E+02	7.08E+02				A
2.511E+02	5.34E+02				A
3.981E+02	3.70E+02				A
6.309E+02	2.44E+02				A
1.000E+03	1.57E+02				A
1.584E+03	9.97E+01				A
2.511E+03	6.31E+01				A
3.981E+03	3.99E+01				A
6.309E+03	2.51E+01				A
1.000E+04	1.58E+01				A
1.584E+04	1.00E+01				A
2.511E+04	6.32E+00				A
3.981E+04	3.99E+00				A
6.309E+04	2.51E+00				A
1.000E+05	1.59E+00				A
1.584E+05	1.00E+00				A
2.511E+05	6.33E-01				A
3.981E+05	3.99E-01				A
6.309E+05	2.52E-01				A
1.000E+06	1.59E-01				A
1.584E+06	1.00E-01				A
2.511E+06	6.33E-02				A
3.981E+06	3.99E-02				A
6.309E+06	2.52E-02				A
1.000E+07	1.59E-02				A
1.584E+07	1.00E-02				A
2.511E+07	6.33E-03				A
3.981E+07	4.00E-03				A
6.309E+07	2.53E-03				A
1.000E+08	1.61E-03				A
1.584E+08	1.03E-03				A
2.511E+08	6.80E-04				A
3.981E+08	4.71E-04				A
6.309E+08	3.55E-04				A
1.000E+09	2.96E-04				A
1.584E+09	2.69E-04				A
2.511E+09	2.57E-04				A
3.981E+09	2.52E-04				A
6.309E+09	2.49E-04				A
1.000E+10	2.44E-04				A
1.584E+10	2.36E-04				A
2.511E+10	2.19E-04				A
3.981E+10	1.88E-04				A
6.309E+10	1.46E-04				A
1.000E+11	1.03E-04				A

7.48



Ignore all r_o 's and capacitances except C_x

$$i_{d1} = \frac{1}{2} g_{m1} V_{id}$$

$$V_{gs4} = -i_{d1} \left(\frac{1}{g_{m3}} \parallel \frac{1}{sC_x} \right)$$

$$= -i_{d1} \frac{1}{g_{m3} + sC_x}$$

$$i_{d4} = g_{m4} V_{gs4}$$

$$i_{d2} = -\frac{1}{2} g_{m2} V_{id}$$

$$g_{m1} = g_{m2}, g_{m3} = g_{m4}$$

$$\therefore i_o = -i_{d2} - i_{d4}$$

$$= \frac{1}{2} g_{m1} V_{id} - g_{m3} V_{gs4}$$

$$= \frac{1}{2} g_{m1} V_{id} + g_{m3} \frac{i_{d1}}{g_{m3} + sC_x}$$

$$= \frac{1}{2} g_{m1} V_{id} + g_{m3} \frac{1}{2} g_{m1} V_{id} \frac{1}{g_{m3} + sC_x}$$

$$= \frac{1}{2} g_{m1} V_{id} \left(1 + \frac{g_{m3}}{g_{m3} + sC_x} \right)$$

$$= g_{m1} V_{id} \frac{1 + sC_x/2g_{m3}}{1 + sC_x/g_{m3}}$$

$$p = -\frac{g_{m3}}{C_x}$$

$$z = -2 \frac{g_{m3}}{C_x}$$

7.49

$$g_{m3} = \frac{2|I_{D3}|}{|V_{ov3}|} = \frac{2 \times 100 \mu A}{0.2 V} = 1 \text{ mA/V}$$

$$p = -\frac{g_{m3}}{C_x} = -\frac{1 \text{ mA/V}}{0.1 \text{ pF}} = -10^{10} \text{ rad/s}$$

$$z = -2 \frac{g_{m3}}{C_x} = -2 \times 10^{10} \text{ rad/s}$$

CHAPTER 8

8.1

$$(a) A = \frac{a}{1+af} = \frac{10^5}{1+100} = 990.1$$

$$\frac{\delta A}{A} = \frac{\delta a}{a} \frac{1}{1+T} = \frac{10}{101} = 0.1\%$$

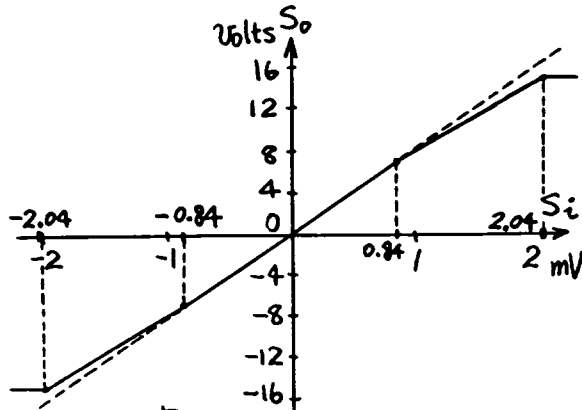
$$(b) A = \frac{10^5}{1+10^4} = 9.999$$

$$\frac{\delta A}{A} = \frac{10}{10,001} = 0.001\%$$

8.2

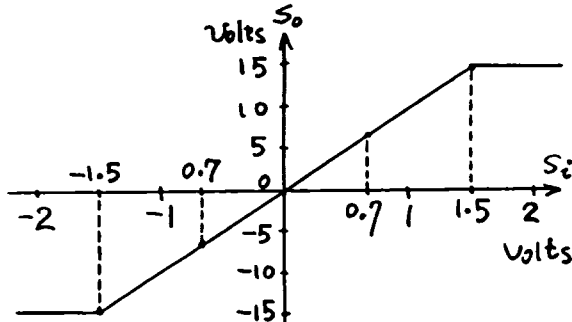
$$(a) A_1 = \frac{a_1}{1+a_1f} = \frac{50000}{1+5} = 8333$$

$$A_2 = \frac{20,000}{1+2} = 6667$$



$$(b) A_1 = \frac{50,000}{1+5000} = 9.998$$

$$A_2 = \frac{20,000}{1+2000} = 9.995$$



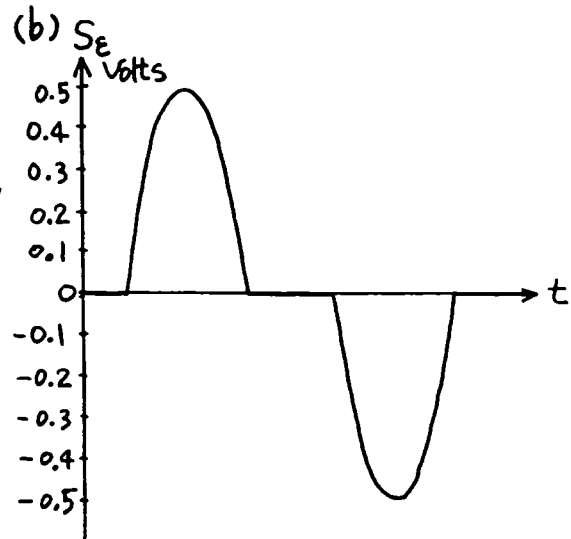
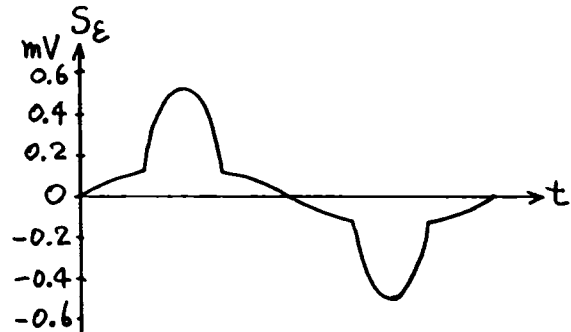
8.3

$$(a) \Delta S_E = \frac{\Delta S_i}{1+af}$$

$$\text{For } |S_i| < 0.7 \text{ V } 1+af = 5001$$

$$\text{For } 0.7 \text{ V} < |S_i| < 1.5 \text{ V } 1+af = 2001$$

$$\text{For } |S_i| > 1.5 \text{ V } 1+af = 1$$



8.4

$$i_i = i_E + i_{fb}$$

$$i_o = a i_E = a (i_i - i_{fb})$$

$$= a i_i - a f i_o$$

$$\therefore \frac{i_o}{i_i} = \frac{a}{1+af} \quad \text{--- (8.40)}$$

8-2

$$v_i = i_e Z_i = \frac{i_o}{a} Z_i = \frac{Z_i}{a} \frac{a}{1+af} i_o$$

$$\therefore Z_i = \frac{v_i}{i_i} = \frac{Z_i}{1+T} \text{ ----- (8.41)}$$

Apply a voltage v_o at the output and open-circuit input

$$i_o = \frac{v_o}{Z_o} + a i_e = \frac{v_o}{Z_o} - a f i_o$$

$$\therefore i_o(1+T) = \frac{v_o}{Z_o}$$

$$\therefore Z_o = \frac{v_o}{i_o} \frac{Z_o}{1+T}$$

8.5

$$v_i = v_e + v_{fb}$$

$$i_o = a v_e = a(v_i - v_{fb})$$

$$= a v_i - a f i_o$$

$$\therefore \frac{i_o}{v_i} = \frac{a}{1+af} \text{ ----- (8.43)}$$

$$i_e = \frac{v_e}{Z_i} = \frac{i_o}{a} \frac{1}{Z_i} = \frac{v_i}{1+af} \frac{1}{Z_i}$$

$$\therefore Z_i = \frac{v_i}{i_e} = Z_i(1+T)$$

Apply a voltage v_o at the output and short-circuit the input

$$i_o = \frac{v_o}{Z_o} + a v_e = \frac{v_o}{Z_o} - a f i_o$$

$$\therefore i_o(1+T) = \frac{v_o}{Z_o}$$

$$\therefore Z_o = \frac{v_o}{i_o} = Z_o(1+T)$$

8.6(a)

From (8.66)

$$Z_{ia} = \frac{R_F Z_i}{R_F + Z_i} = \frac{100 \times 500}{600} = 83.3 \text{ k}\Omega$$

From (8.68)

$$Z_{oa} = Z_o \parallel R_F \parallel R_L$$

$$= 200 \parallel 100 \text{ k} \parallel 15 \text{ k}$$

$$\approx 200 \Omega$$

From (8.70)

$$T = \left(\frac{10^5 \times 15 \times 10^3}{10^5 \times 15 \times 10^3 + 200 \times 10^3 + 200 \times 15 \times 10^3} \right) \times 75,000$$

$$\times \frac{500}{600}$$

$$= 61,560$$

Thus with feedback

$$Z_i = \frac{83.3 \text{ k}}{61,560} = 1.4 \Omega$$

$$Z_o = \frac{200}{61,560} = 0.0032 \Omega$$

$$A = \frac{1}{f} \frac{1}{1 + \frac{1}{T}} = \frac{100 \text{ k}\Omega}{1 + \frac{1}{61,560}}$$

$$= 99.998 \text{ k}\Omega$$

8.6(b)

$$R = \frac{R_L \parallel (R_F + Z_i)}{Z_o + R_L \parallel (R_F + Z_i)} \frac{Z_i}{Z_i + R_F} a_v$$

$$= \frac{15k \parallel (100k + 500k)}{200 + 15k \parallel (100k + 500k)} \frac{500k}{500k + 100k} 75000$$

$$= 6.16 \times 10^4$$

$$A_{ov} = -R_F = -100k\Omega$$

$$d = \frac{V_o}{i_i} \Big|_{a_v=0} = \frac{Z_i}{Z_i + [R_F + Z_o \parallel R_L]} (Z_o \parallel R_L)$$

$$= \frac{500k}{500k + 100k + 200 \parallel 15k} (200 \parallel 15k)$$

$$= 160\Omega$$

$$A = A_{ov} \frac{R}{1+R} + \frac{d}{1+R}$$

$$= -100k \frac{6.16 \times 10^4}{1 + 6.16 \times 10^4} + \frac{160}{1 + 6.16 \times 10^4}$$

$$= -99.9983k\Omega$$

$$R_{in}(a_v=0) = Z_i \parallel (R_F + Z_o \parallel R_L)$$

$$= 500k \parallel (100k + 200 \parallel 15k) = 83k\Omega$$

$$R(\text{short input}) = 0$$

$$R(\text{open input}) = R = 6.16 \times 10^4$$

$$R_{in} = R_{in}(a_v=0) \frac{1+R(\text{short})}{1+R(\text{open})} = 83k \frac{1+0}{1+6.16 \times 10^4}$$

$$= 1.3\Omega$$

$$R_{out}(a_v=0) = R_L \parallel Z_o \parallel (R_F + Z_i)$$

$$= 15k \parallel 200 \parallel (100k + 500k) = 197\Omega$$

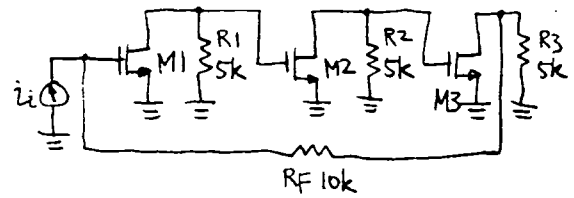
$$R(\text{short output}) = 0$$

$$R(\text{open output}) = R = 6.16 \times 10^4$$

$$R_{out} = R_{out}(a_v=0) \frac{1+R(\text{short})}{1+R(\text{open})}$$

$$= 197 \frac{1+0}{1+6.16 \times 10^4} = 3.2 \times 10^{-3}\Omega = 3.2m\Omega$$

8.7

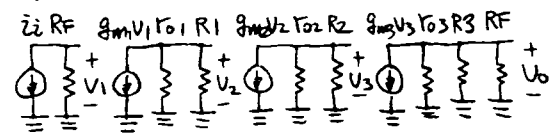


$$g_m = \sqrt{2k' \frac{W}{L} I_D} = \sqrt{2 \times 60 \times 10^{-6} \times 100 \times 10^{-3}}$$

$$= 3.5 \times 10^{-3} A/V$$

$$r_{o1} = \frac{1}{\lambda I_D} = \frac{50}{10^{-3}} = 50k\Omega$$

(a)



$$A = \frac{V_o}{i_i} \Big|_{f=0} = R_F (-g_{m1}(r_{o1} \parallel R_1)) (-g_{m2}(r_{o2} \parallel R_2)) (-g_{m3}(r_{o3} \parallel R_3 \parallel R_F))$$

$$= -g_{m1}^3 (r_{o1} \parallel R_1)^2 R_F (r_{o3} \parallel R_3 \parallel R_F)$$

$$= -(3.5 \times 10^{-3})^3 (50k \parallel 15k)^2 10k (50k \parallel 5k \parallel 10k)$$

$$= -2.76 \times 10^7 \Omega$$

$$f = -\frac{z_{fs}}{V_o} = -\frac{1}{R_F} = -\frac{1}{10k\Omega}$$

$$a_f = 2.76 \times 10^3$$

$$\frac{V_o}{i_i} = \frac{a}{1+a_f} = \frac{-2.76 \times 10^7}{1+2.76 \times 10^3} = -10k\Omega$$

$$R_i = \frac{R_F}{1+a_f} = \frac{10k}{1+2.76 \times 10^3} = 16.4\Omega$$

$$R_o = \frac{r_{o3} \parallel R_3 \parallel R_F}{1+a_f} = \frac{50k \parallel 5k \parallel 10k}{1+2.76 \times 10^3} = 1.13\Omega$$

(b)

$$A = -2.76 \times 10^7 \frac{R_F \parallel R_3}{R_F} = -2.76 \times 10^7 \frac{10k \parallel 1k}{10k}$$

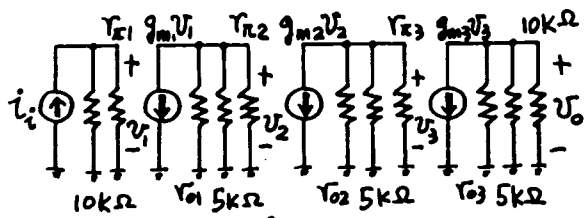
$$= -2.51 \times 10^6 \Omega$$

$$a_f = 251$$

$$R_o = \frac{r_{o3} \parallel R_3 \parallel R_F}{1+a_f} = \frac{50k \parallel 5k \parallel 10k}{1+251} = 12.4\Omega$$

8.8

(a) Basic amplifier



$$r_{\pi 1} = r_{\pi 2} = r_{\pi 3} = \frac{\beta}{g_m} = 5.2 \text{ k}\Omega$$

$$g_m = \frac{1}{26} \text{ V}, r_o = 50 \text{ k}\Omega$$

$$R_1 = 10 \text{ k}\Omega \parallel r_{\pi 1} = \frac{5.2 \times 10}{15.2} = 3.42 \text{ k}\Omega$$

$$R_2 = r_{o1} \parallel 5 \text{ k}\Omega \parallel r_{\pi 2} = 2.42 \text{ k}\Omega$$

$$R_3 = r_{o2} \parallel 5 \text{ k}\Omega \parallel r_{\pi 3} = 2.42 \text{ k}\Omega$$

$$R_4 = r_{o3} \parallel 5 \text{ k}\Omega \parallel 10 \text{ k}\Omega = 3.13 \text{ k}\Omega$$

$$\begin{aligned} \therefore \frac{v_o}{i_i} &= -R_1 g_{m1} R_2 g_{m2} R_3 g_{m3} R_4 \\ &= -3.42 \frac{2420}{26} \frac{2420}{26} \frac{3130}{26} \text{ k}\Omega \\ &= -3.57 \times 10^9 \Omega = a \end{aligned}$$

$$f = -\frac{i_{fb}}{v_o} = -\frac{1}{10 \text{ k}\Omega}$$

$$\begin{aligned} \therefore \text{overall } \frac{v_o}{i_i} &= \frac{a}{1+af} = \frac{-3.57 \times 10^9}{1+3.57 \times 10^5} \\ &= -10 \text{ k}\Omega \end{aligned}$$

$$\text{loop gain} = af = 3.57 \times 10^5$$

$$R_i = \frac{R_1}{1+af} = \frac{3420}{1+3.57 \times 10^5} = 0.0096 \Omega$$

$$R_o = \frac{R_4}{1+af} = \frac{3130}{1+3.57 \times 10^5} = 0.0088 \Omega$$

(b)

$$\text{New value of } R_1 = 3.42 \text{ k}\Omega \parallel 1 \text{ k}\Omega = 774 \Omega$$

$$\therefore a = -3.57 \times 10^9 \frac{774}{3420} = -808 \text{ M}\Omega$$

$$\therefore af = 808 \times 10^6 \times 10^{-4} = 8.08 \times 10^4$$

$$R_o = \frac{R_4}{1+af} = \frac{3130}{1+8.08 \times 10^4} = 0.0387 \Omega$$

8-5

8.9

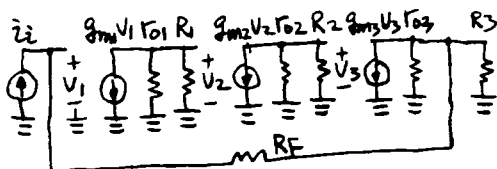
 g_{m1} , r_{o1} are the same as in Problem 8.7

(a)

$$\begin{aligned}
 R &= (r_{o3} \parallel R_3)(-g_{m1})(r_{o1} \parallel R_1)(-g_{m2})(r_{o2} \parallel R_2)g_{m3} \\
 &= [g_{m1}(r_{o1} \parallel R_1)]^3 = [3.5 \times 10^{-3}(50k \parallel 5k)]^3 \\
 &= 4.03 \times 10^3
 \end{aligned}$$

$$A_{vo} = -R_F = -10k\Omega$$

$$d = \left. \frac{v_o}{i_i} \right|_{g_{m3}=0} = r_{o3} \parallel R_3 = 50k \parallel 5k = 4.54k\Omega$$



$$A = A_{vo} \frac{R}{1+R} + \frac{d}{1+R}$$

$$= -10k \frac{4.03 \times 10^3}{1+4.03 \times 10^3} + \frac{4.54k}{1+4.03 \times 10^3} = -10k\Omega$$

$$R_{in}(g_{m3}=0) = R_F + (r_{o3} \parallel R_3)$$

$$= 10k + (50k \parallel 5k) = 14.5k$$

$$R(\text{short}) = 0$$

$$R(\text{open}) = R = 4.03 \times 10^3$$

$$R_{in} = R_{in}(g_{m3}=0) \frac{1+R(\text{short})}{1+R(\text{open})}$$

$$= 14.5k \frac{1+0}{1+4.03 \times 10^3} = 3.60\Omega$$

$$R_{out}(g_{m3}=0) = r_{o3} \parallel R_3 = 50k \parallel 5k = 4.54k$$

$$R(\text{short}) = 0$$

$$R(\text{open}) = R = 4.03 \times 10^3$$

$$R_{out} = R_{out}(g_{m3}=0) \frac{1+R(\text{short})}{1+R(\text{open})}$$

$$= 4.54k \frac{1+0}{1+4.03 \times 10^3} = 1.13\Omega$$

(b)

Replace $r_{o3} \parallel R_3 = 4.54k\Omega$ with

$$\left[r_{o3} \parallel R_3 \parallel (R_F + R_S) \right] \frac{R_S}{R_F + R_S}$$

$$= [50k \parallel 5k \parallel (10k + 1k)] \frac{1k}{10k + 1k}$$

$$= 292\Omega$$

$$R(\text{open}) = 4.03 \times 10^3 \frac{292}{4.54k} = 259$$

$$R(\text{short}) = 0$$

$$R_{out}(g_{m3}=0) = r_{o3} \parallel R_3 \parallel (R_F + R_S)$$

$$= 50k \parallel 5k \parallel (10k + 1k) = 3.22k$$

$$R_{out} = 3.22k \frac{1+0}{1+259} = 12.4\Omega$$

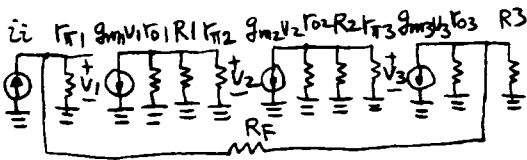
8-6

8.10

$$g_{m1} = \frac{I_c}{V_T} = \frac{1\text{mA}}{26\text{mV}} = 3.85 \times 10^{-2} \text{ A/V}$$

$$r_{o1} = \frac{V_A}{I_c} = \frac{50}{10^{-3}} = 50 \text{ k}\Omega$$

$$r_{\pi 1} = \frac{\beta}{g_{m1}} = \frac{100}{3.85 \times 10^{-2}} = 5.2 \text{ k}\Omega$$



(a)

$$R = [r_{o3} \parallel R_3 \parallel (R_F + r_{\pi 1})] \frac{r_{\pi 1}}{R_F + r_{\pi 1}} (-g_{m1})$$

$$(r_{o1} \parallel R_1 \parallel r_{\pi 2}) (-g_{m2}) (r_{o2} \parallel R_2 \parallel r_{\pi 3}) g_{m3}$$

$$= g_{m1}^3 \left[(r_{o1} \parallel R_1 \parallel r_{\pi 2})^2 [r_{o3} \parallel R_3 \parallel (R_F + r_{\pi 1})] \right]$$

$$\frac{r_{\pi 1}}{R_F + r_{\pi 1}}$$

$$= (3.85 \times 10^{-2})^3 [50 \text{ k} \parallel 5 \text{ k} \parallel 5.2 \text{ k}]^2$$

$$\frac{5.2 \text{ k}}{[50 \text{ k} \parallel 5 \text{ k} \parallel (10 \text{ k} + 5.2 \text{ k})] 10 \text{ k} + 5.2 \text{ k}}$$

$$= 4.00 \times 10^5$$

$$A_{\infty} = -R_F = -10 \text{ k}\Omega$$

$$d = \frac{v_o}{i_i} \bigg|_{g_{m3}=0} = \frac{r_{\pi 1}}{r_{\pi 1} + [R_F + (r_{o3} \parallel R_3)]} (r_{o3} \parallel R_3)$$

$$= \frac{5.2 \text{ k}}{5.2 \text{ k} + [10 \text{ k} + (50 \text{ k} \parallel 5 \text{ k})]} (50 \text{ k} \parallel 5 \text{ k})$$

$$= 1.20 \text{ k}\Omega$$

$$A = A_{\infty} \frac{R}{1+R} + \frac{d}{1+R}$$

$$= -10 \text{ k} \frac{4.00 \times 10^5}{1 + 4.00 \times 10^5} + \frac{1.20 \text{ k}}{1 + 4.00 \times 10^5}$$

$$= -10 \text{ k}\Omega$$

$$R_{in}(g_{m3}=0) = r_{\pi 1} \parallel [R_F + (r_{o3} \parallel R_3)]$$

$$= 5.2 \text{ k} \parallel [10 \text{ k} + (50 \text{ k} \parallel 5 \text{ k})] = 3.83 \text{ k}\Omega$$

$$R(\text{short}) = 0$$

$$R(\text{open}) = R = 4.00 \times 10^5$$

$$R_{in} = R_{in}(g_{m3}=0) \frac{1+R(\text{short})}{1+R(\text{open})}$$

$$= 3.83 \text{ k} \frac{1+0}{1+4.00 \times 10^5}$$

$$= 9.60 \text{ m}\Omega$$

$$R_{out}(g_{m3}=0) = (R_F + r_{\pi 1}) \parallel r_{o3} \parallel R_3$$

$$= (10 \text{ k} + 5.2 \text{ k}) \parallel 50 \text{ k} \parallel 5 \text{ k}$$

$$= 3.50 \text{ k}\Omega$$

$$R(\text{short}) = 0$$

$$R(\text{open}) = R = 4.00 \times 10^5$$

$$R_{out} = R_{out}(g_{m3}=0) \frac{1+R(\text{short})}{1+R(\text{open})}$$

$$= 3.50 \text{ k} \frac{1+0}{1+4.00 \times 10^5}$$

$$= 8.75 \text{ m}\Omega$$

(b)

$$R_{out}(g_{m3}=0) = [R_F + (R_S \parallel r_{\pi 1})] \parallel r_{o3} \parallel R_3$$

$$= [10 \text{ k} + (1 \text{ k} \parallel 5.2 \text{ k})] \parallel 50 \text{ k} \parallel 5 \text{ k}$$

$$= 3.20 \text{ k}\Omega$$

$$R(\text{short}) = 0$$

$$\text{Replace } r_{\pi 1} = 5.2 \text{ k}\Omega \text{ with}$$

$$R_S \parallel r_{\pi 1} = 1 \text{ k} \parallel 5.2 \text{ k} = 839 \Omega$$

$$R(\text{open}) = (3.85 \times 10^{-2})^3 [50 \text{ k} \parallel 5 \text{ k} \parallel 5.2 \text{ k}]^2$$

$$\frac{839}{[50 \text{ k} \parallel 5 \text{ k} \parallel (10 \text{ k} + 839)] 10 \text{ k} + 839}$$

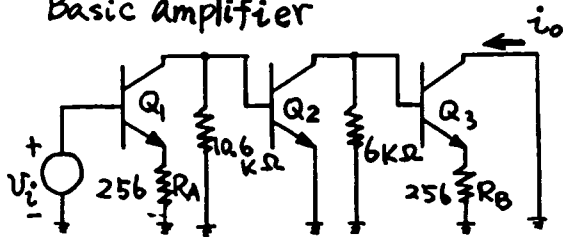
$$= 8.28 \times 10^4$$

$$R_{out} = 3.20 \text{ k} \frac{1+0}{1+8.28 \times 10^4}$$

$$= 38.7 \text{ m}\Omega$$

8.11

Basic amplifier



$$R_{E1} \parallel (R_F + R_{E2}) = 290 \parallel 2.19k = 256\Omega$$

$$r_{\pi 1} = \frac{\beta}{g_{m1}} = 52 \times 120 = 6.24 k\Omega$$

$$r_{o1} = 80 k\Omega$$

$$r_{\pi 2} = \frac{26 \times 120}{0.77} = 4.05 k\Omega$$

$$r_{o2} = \frac{40}{0.77} = 52 k\Omega$$

$$r_{\pi 3} = \frac{26 \times 120}{0.73} = 4.27 k\Omega$$

$$r_{o3} = \frac{40}{0.73} = 54.8 k\Omega$$

In forward gain calculation, neglect r_{o1} and r_{o3} .

For the basic amplifier,

$$\frac{i_o}{v_i} = \frac{g_{m1}}{1 + g_{m1}R_A} R_1 g_{m2} R_2 \frac{g_{m3}}{1 + g_{m3}R_B}$$

$$R_1 = 10.6k \parallel r_{\pi 2} = 2.93 k\Omega$$

$$R_2 = r_{o2} \parallel 6k \parallel R_{i3}$$

$$R_{i3} = r_{\pi 3} (1 + g_{m3}R_B)$$

$$= 4.27 \left(1 + \frac{0.73}{26} \times 256 \right)$$

$$= 35 k\Omega$$

$$\therefore R_2 = 52k \parallel 6k \parallel 35k = 4.66 k\Omega$$

$$\therefore \frac{i_o}{v_i} = \frac{1}{52} \frac{1}{1 + \frac{356}{52}} 2930 \frac{0.77}{26} 4660 \times \frac{0.73}{26} \frac{1}{8.19}$$

$$\therefore a = 4.5 A/V$$

From (8.95)

$$f = \frac{1}{\alpha_3} \frac{R_{E1} R_{E2}}{R_{E1} + R_{E2} + R_F}$$

$$= \frac{1}{0.99} \frac{290 \times 290}{290 + 290 + 1900}$$

$$= 34.25 \Omega$$

$$\therefore \text{loop gain} = af = 4.5 \times 34.25 = 154$$

Overall gain with feedback

$$= \frac{a}{1 + af} = \frac{4.5}{1 + 154} = \frac{4.5}{155} A/V$$

$$\therefore \frac{i_o}{v_i} = 29 mA/V$$

For the basic amplifier

Input resistance

$$r_{ia} = r_{\pi 1} (1 + g_{m1}R_A)$$

$$= 6.24 \left(1 + \frac{256}{52} \right) = 36.96 k\Omega$$

Output resistance

$$r_{oa} = r_{o3} \left(1 + g_{m3}R_B \frac{r_{\pi 3}}{r_{\pi 3} + R_{S3}} \right)$$

$$R_{S3} = r_{o2} \parallel 6k = 5.38 k\Omega$$

$$\therefore r_{oa} = 54.8 \left(1 + \frac{0.73}{26} 256 \frac{4.27}{4.27 + 5.38} \right)$$

$$= 229 k\Omega$$

For the feedback amplifier

$$R_i = r_{ia} (1 + af) = 36.96 \times 155 = 5.73 M\Omega$$

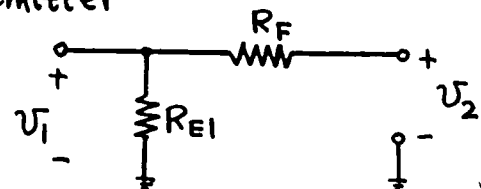
$$R_o = r_{oa} (1 + af) = 229 \times 155 = 35.5 M\Omega$$

8.12

For the basic amplifier

$$\frac{v_o}{v_i} = \frac{i_o}{v_i} R_B = 4.5 \times 256 = 1152$$

where v_o is the voltage at Q_3 emitter



$$f = h_{12}f = \frac{v_i}{v_o} = \frac{R_{E1}}{R_{E1} + R_F}$$

$$= \frac{290}{290 + 1900} = 0.132$$

$$\therefore \text{loop gain} = af = 1152 \times 0.132 = 152$$

as in 8.8

$\therefore$ with feedback, overall gain is

$$\frac{v_o}{v_i} = \frac{a}{1+af} = \frac{1152}{1+152} = 7.53$$

Input resistance i_s

$$R_i = r_{ia}(1+af) = 36.96 \times 153 = 5.65 \text{ M}\Omega \text{ as in 8.8}$$

Output resistance

$$R_o = \frac{r_{oa}}{1+af}$$

$$\begin{aligned} r_{oa} &= 256 \parallel \left(\frac{1}{g_{m3}} + \frac{R_{s3}}{\beta_3} \right) \\ &= 256 \parallel \left(36 + \frac{5380}{120} \right) \\ &= 256 \parallel 81 = 61.5 \Omega \end{aligned}$$

$\therefore$ with feedback

$$R_o = \frac{61.5}{153} = 0.4 \Omega$$

8.13

Bias

$$I_{c1} + I_{c2} = \frac{5.3}{5} = 1.06 \text{ mA}$$

$$I_{c1} = \frac{V_{BE3}}{1.25} = \frac{0.7}{1.25} = 0.56 \text{ mA}$$

$$\therefore I_{c2} = 0.5 \text{ mA}$$

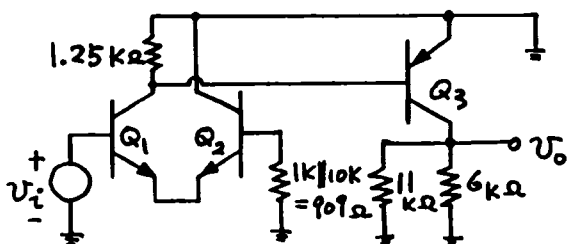
$$I_{c3} = \frac{6V}{6 \text{ k}\Omega} = 1 \text{ mA for } v_o|_{dc} = 0$$

Assume $I_{c1} = I_{c2} = 0.53 \text{ mA}$

$$\text{Then } r_{\pi 1} = r_{\pi 2} = \frac{200 \times 26}{0.53} = 9.81 \text{ k}\Omega$$

$$r_{\pi 3} = 2.6 \text{ k}\Omega$$

Basic amplifier



$$\frac{v_o}{v_i} = \frac{g_{m1}}{1+g_{m1}R_{E1}} R_1 g_{m3} R_2$$

$$\begin{aligned} R_{E1} &= \frac{1}{g_{m2}} + \frac{909}{\beta_2} = \frac{26}{0.53} + \frac{909}{200} \\ &= 54 \Omega \end{aligned}$$

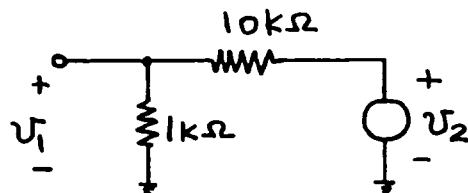
$$R_1 = 1.25 \text{ k}\Omega \parallel r_{\pi 3} = 844 \Omega$$

$$R_2 = 6 \text{ k}\Omega \parallel 11 \text{ k}\Omega = 3.88 \text{ k}\Omega$$

$$\therefore \frac{v_o}{v_i} = \frac{0.53}{26} \frac{1}{1 + \frac{0.53}{26} 54} 844 \frac{3880}{26}$$

$$\therefore a = 1222$$

$$f = h_{12}f = \frac{v_1}{v_2} = \frac{1}{11}$$



$$\therefore \text{loop gain} = \frac{1222}{11} = 111$$

$\therefore$ with feedback gain

$$\frac{v_o}{v_i} = \frac{1222}{1+111} = 10.9$$

For the basic amplifier

$$r_{oa} = 11 \text{ k}\Omega \parallel 6 \text{ k}\Omega = 3.88 \text{ k}\Omega$$

$$r_{ia} = r_{\pi 1} (1 + g_{m1} R_{E1})$$

$$= 9.81 \left(1 + \frac{0.53}{26} 54 \right) = 20.6 \text{ k}\Omega$$

With feedback

$$R_o = \frac{3880}{112} = 34.6 \Omega$$

$$R_i = 20.6 \times 112 = 2.3 \text{ M}\Omega$$

8-9

```

FEEDBACK AMP
VCC 1 0 6V
VEE 2 0 -6V
RL 1 3 1.25K
Q1 3 5 4 NPN
Q2 1 6 4 NPN
REE 4 2 5K
Q3 7 3 1 PNP
RBIAS 7 2 6K
RF 7 6 10K
RE 6 0 1K
.MODEL NPN NPN BF=200 IS=1E-15
.MODEL PNP PNP BF=100 IS=1E-15
VI 5 0 SIN 0 0.25 10K 0 0
.TRAN 4US 200US
.PLOT TRAN V(7)
.FOUR 10K V(7)
.DC VI -1 1 0.05
.PLOT DC V(7)
.TF V(7) VI
.OPTIONS HOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** DC TRANSFER CURVES TNOM= 27.000 TEMP= 27.000

VOLT	V(7)
(A) -5.000E+00	0.
5.000E+00	1.000E+01
1.500E+01	
-1.000E+00	-3.88E+00
-9.500E-01	-3.88E+00
-9.000E-01	-3.88E+00
-8.500E-01	-3.88E+00
-8.000E-01	-3.88E+00
-7.500E-01	-3.88E+00
-7.000E-01	-3.88E+00
-6.500E-01	-3.88E+00
-6.000E-01	-3.88E+00
-5.500E-01	-3.88E+00
-5.000E-01	-3.88E+00
-4.500E-01	-3.88E+00
-4.000E-01	-3.88E+00
-3.500E-01	-3.81E+00
-3.000E-01	-3.31E+00
-2.500E-01	-2.77E+00
-2.000E-01	-2.23E+00
-1.500E-01	-1.68E+00
-1.000E-01	-1.13E+00
-5.000E-02	-5.86E-01
0.	-3.50E-02
5.000E-02	5.17E-01
1.000E-01	1.06E+00
1.500E-01	1.62E+00
2.000E-01	2.17E+00
2.500E-01	2.72E+00
3.000E-01	3.27E+00
3.500E-01	3.83E+00
4.000E-01	4.38E+00
4.500E-01	4.93E+00
5.000E-01	5.49E+00
5.500E-01	5.91E+00
6.000E-01	5.94E+00
6.500E-01	5.95E+00
7.000E-01	5.95E+00
7.500E-01	5.95E+00
8.000E-01	5.95E+00
8.500E-01	5.95E+00
9.000E-01	5.95E+00
9.500E-01	5.95E+00
1.000E+00	5.95E+00

***** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

```

+0:1      = 6.000E+00 0:2      = -6.000E+00 0:3      = 5.285E+00
+0:4      = -7.006E-01 0:5      = 0.          0:6      = -5.331E-03
+0:7      = -3.498E-02

```

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	Q1	Q2	Q3
MODEL	0:NPN	0:NPN	0:PNP
IB	2.907E-06	2.366E-06	-9.912E-06
IC	5.815E-04	4.731E-04	-9.912E-04
VEE	7.006E-01	6.953E-01	-7.144E-01
VCE	5.986E+00	6.700E+00	-6.035E+00
VBC	-5.285E+00	-6.005E+00	5.320E+00
VS	-5.285E+00	-6.000E+00	-5.285E+00
POWER	3.483E-03	3.172E-03	5.989E-03
BETAD	2.000E+02	2.000E+02	1.000E+02
GM	2.248E-02	1.829E-02	3.832E-02
RPI	8.896E+03	1.093E+04	2.609E+03
RX	0.	0.	0.
RO	5.285E+15	6.005E+15	5.320E+15
CPI	0.	0.	0.
CMU	0.	0.	0.
CBX	0.	0.	0.

```

CCS      0.          0.          0.
BETAC    2.000E+02  2.000E+02  9.999E+01
FT       3.578E+12  2.911E+12  6.099E+12

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(7)/VI      = 1.102E+01
INPUT RESISTANCE AT VI      = 2.280E+06
OUTPUT RESISTANCE AT V(7)   = 3.507E+01

```

***** TRANSIENT ANALYSIS TNOM= 27.000 TEMP= 27.000

TIME	V(7)
(A) -5.000E+00	-2.000E+00
0.	0.
2.000E+00	4.000E+00
4.000E+00	6.51E-01
8.000E+00	1.29E+00
1.200E+01	1.85E+00
1.600E+01	2.29E+00
2.000E+01	2.57E+00
2.400E+01	2.71E+00
2.800E+01	2.67E+00
3.200E+01	2.46E+00
3.600E+01	2.09E+00
4.000E+01	1.57E+00
4.400E+01	9.73E-01
4.800E+01	3.08E-01
5.200E+01	-3.80E-01
5.600E+01	-1.04E+00
6.000E+01	-1.64E+00
6.400E+01	-2.14E+00
6.800E+01	-2.52E+00
7.200E+01	-2.73E+00
7.600E+01	-2.77E+00
8.000E+01	-2.62E+00
8.400E+01	-2.34E+00
8.800E+01	-1.91E+00
9.200E+01	-1.36E+00
9.600E+01	-7.20E-01
1.000E+02	-3.50E-02

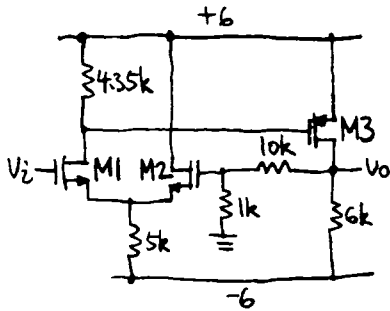
FOURIER COMPONENTS OF TRANSIENT RESPONSE V(7)

DC COMPONENT = -3.122D-02

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	2.744E+00	1.000E+00	-7.176E-03	0.
2	2.000E+04	4.050E-03	1.476E-03	-8.646E+01	-8.645E+01
3	3.000E+04	6.302E-04	2.297E-04	1.017E+02	1.017E+02
4	4.000E+04	3.677E-04	1.340E-04	8.741E+01	8.741E+01
5	5.000E+04	9.451E-04	3.444E-04	1.441E+02	1.441E+02
6	6.000E+04	5.495E-05	2.003E-05	-9.498E+01	-9.497E+01
7	7.000E+04	5.195E-04	1.893E-04	-1.563E+02	-1.563E+02
8	8.000E+04	1.778E-05	6.478E-06	1.607E+01	1.607E+01
9	9.000E+04	2.990E-03	1.090E-03	-1.997E+01	-1.996E+01

TOTAL HARMONIC DISTORTION = 1.895E-01 PERCENT

8.14



$$I_{D1} = \frac{k_n'}{2} \frac{W}{L} (0 - V_{S12} - V_{tn})^2$$

$$= \frac{60 \times 10^{-6}}{2} 100 (-V_{S12} - 1)^2 = 3 \times 10^{-3} (V_{S12} + 1)^2$$

$$I_{D2} = \frac{k_n'}{2} \frac{W}{L} (V_{G2} - V_{S2} - V_{tn})^2$$

$$= 3 \times 10^{-3} (V_{G2} - V_{S2} - 1)^2$$

$$V_{S12} = -6 + 5k(I_{D1} + I_{D2})$$

$$|V_{GSS}| = 4.35k I_{D1}$$

$$I_{D3} = \frac{k_p'}{2} \frac{W}{L} (|V_{GSS}| - |V_{tp}|)^2$$

$$= \frac{20 \times 10^{-6}}{2} 100 (|V_{GSS}| - 1)^2 = 10^{-3} (|V_{GSS}| - 1)^2$$

$$V_0 = -6 + 6k I_{D3}$$

$$V_{G2} = \frac{1k}{10k + 1k} V_0 = \frac{1}{11} V_0$$

Assuming $V_0 = V_{G2} = 0V$, iteratively solve the equations

$$V_{S12} = -1.39V, V_0 = V_G = 0V,$$

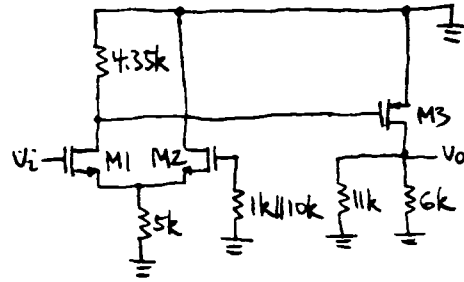
$$I_{D1} = I_{D2} = 0.46mA, I_{D3} = 1mA$$

$$g_{m1} = g_{m2} = \sqrt{2k_n' \frac{W}{L} I_D}$$

$$= \sqrt{2 \times 60 \times 10^{-6} \times 100 \times 0.46 \times 10^{-3}} = 2.3 \times 10^{-3} A/V$$

$$g_{m3} = \sqrt{2k_p' \frac{W}{L} I_D} = \sqrt{2 \times 20 \times 10^{-6} \times 100 \times 10^{-3}}$$

$$= 2 \times 10^{-3} A/V$$



The $1k \parallel 10k$ resistance at the gate of M2 is effectively a short circuit since $I_{G2} = 0$

$$R_{S1} = \frac{1}{g_{m2}} \parallel 5k = \frac{1}{2.3 \times 10^{-3}} \parallel 5k = 435 \parallel 5k$$

$$= 400$$

$$\frac{V_0}{V_i} = \frac{g_{m1}}{1 + g_{m1} R_{S1}} R_1 g_{m3} R_2$$

$$= \frac{2.3 \times 10^{-3}}{1 + 2.3 \times 10^{-3} \times 400} 4.35k \times 2 \times 10^{-3} \times (11k \parallel 6k)$$

$$= 40$$

$$f = \frac{1k}{10k + 1k} = \frac{1}{11}$$

$$\text{loop gain } af = 40 \times \frac{1}{11} = 3.6$$

$$A = \frac{a}{1 + af} = \frac{40}{1 + 3.6} = 8.7$$

$$r_{ia} \rightarrow \infty$$

$$r_{oa} = 11k \parallel 6k = 3.9k\Omega$$

$$R_i = (1 + af) r_{ia} \rightarrow \infty$$

$$R_o = \frac{r_{oa}}{1 + af} = \frac{3.9k}{1 + 3.6} = 850\Omega$$

FEEDBACK AMPLIFIER

```

VDD 1 0 6
VSS 2 0 -6
VI 5 0 SIN (0 0.25 10K) AC 1
M1 3 5 4 4 CMOSN W=100U L=1U
M2 1 6 4 4 CMOSN W=100U L=1U
M3 7 3 1 1 CMOSF W=100U L=1U
RL 1 3 4.35K
RSS 4 2 5K
RE 6 0 1K
RF 6 7 10K
RBIAS 7 2 6K
.MODEL CMOSN NMOS VTO=1 KP=60U LAMDA=0
.MODEL CMOSF PMOS VTO=-1 KP=20U LAMDA=0
.OPTIONS NOMOD
.TF V(7) VI
.DC VI -1 1 0.1
.PLOT DC V(7)
.TRAN 5U 200U
.FOUR 10K V(7)
.WIDTH OUT=80
.OPTIONS SPICE
.END

```

***** DC TRANSFER CURVES THOM= 27.000 TEMP= 27.000

VOLT	V(7)
(A)	-5.000E+00 0. 5.000E+00 1.000E+01 1.500E+01
-1.000E+00	-3.88E+00
-9.000E-01	-3.88E+00
-8.000E-01	-3.88E+00
-7.000E-01	-3.88E+00
-6.000E-01	-3.88E+00
-5.000E-01	-3.88E+00
-4.000E-01	-3.32E+00
-3.000E-01	-2.59E+00
-2.000E-01	-1.77E+00
-1.000E-01	-9.03E-01
0.	7.85E-03
1.000E-01	9.47E-01
2.000E-01	1.90E+00
3.000E-01	2.88E+00
4.000E-01	3.87E+00
5.000E-01	4.81E+00
6.000E-01	5.22E+00
7.000E-01	5.41E+00
8.000E-01	5.52E+00
9.000E-01	5.59E+00
1.000E+00	5.63E+00

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

+0:1	= 6.000E+00 0:2	= -6.000E+00 0:3	= 3.999E+00
+0:4	= -1.391E+00 0:5	= 0. 0:6	= 7.140E-04
+0:7	= 7.854E-03		

*** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(7)/VI	= 9.262E+00
INPUT RESISTANCE AT VI	= 9.999E+19
OUTPUT RESISTANCE AT V(7)	= 8.691E+02

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(7)

DC COMPONENT = 5.318D-02

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	2.291E+00	1.000E+00	-7.659E-03	0.
2	2.000E+04	4.535E-02	1.979E-02	-8.974E+01	-8.974E+01
3	3.000E+04	4.182E-03	1.825E-03	7.000E+00	7.000E+00
4	4.000E+04	7.555E-04	3.297E-04	9.087E+01	9.087E+01
5	5.000E+04	8.457E-04	3.690E-04	1.459E+02	1.459E+02
6	6.000E+04	1.723E-04	7.520E-05	-1.101E+02	-1.101E+02
7	7.000E+04	4.216E-04	1.840E-04	-1.537E+02	-1.537E+02
8	8.000E+04	2.989E-05	1.304E-05	9.134E+01	9.134E+01
9	9.000E+04	2.487E-03	1.085E-03	-1.988E+01	-1.988E+01

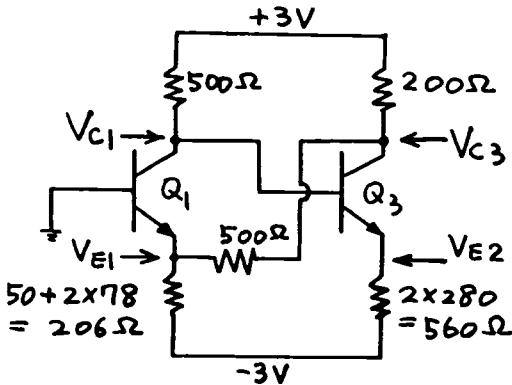
TOTAL HARMONIC DISTORTION = 1.991E+00 PERCENT

8.15

(a)

Bias

Common-mode, half-circuit



$$V_{E1} = -0.7V$$

 ΣI at emitter of Q_1

$$\therefore I_{C1} + \frac{V_{C3} + 0.7}{500} = \frac{2.3}{206} \quad \text{----- (1)}$$

$$V_{C1} = 3 - 500 I_{C1}$$

$$\therefore V_{E3} = V_{C1} - 0.7 = 2.3 - 500 I_{C1}$$

$$\therefore I_{C3} = \frac{3 + V_{E2}}{560} = \frac{5.3 - 500 I_{C1}}{560}$$

$$V_{C3} = 3 - 200 \left(I_{C3} + \frac{V_{C3} + 0.7}{500} \right)$$

$$\therefore 1.4 V_{C3} = 2.72 - 200 \frac{5.3 - 500 I_{C1}}{560}$$

$$= 2.72 - 1.89 + 178 I_{C1}$$

$$\therefore V_{C3} = 0.59 + 127 I_{C1}$$

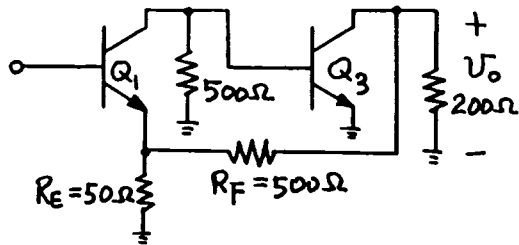
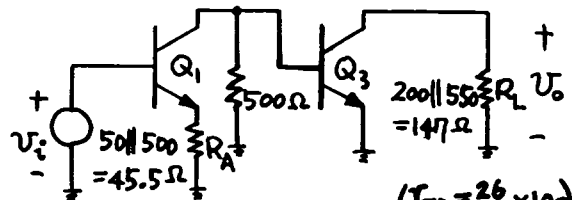
$$\text{In (1)} \quad I_{C1} + \frac{1.29}{500} + \frac{127}{500} I_{C1} = \frac{2.3}{206}$$

$$\therefore I_{C1} = 6.85 \text{ mA}$$

$$I_{C3} = \frac{5.3 - 500 I_{C1}}{560} = 3.3 \text{ mA}$$

(b)

Differential-mode, half-circuit

Basic amplifierBasic amplifier gain $\left(r_{\pi 3} = \frac{26}{3.3} \times 100 = 788 \right)$

$$\frac{V_o}{V_i} \approx \frac{g_{m1}}{1 + g_{m1} R_A} R_1 \frac{r_{\pi 3}}{r_{\pi 3} + r_b} g_{m3} R_L$$

$$R_1 = 500 \parallel (r_{\pi 3} + r_b) = 500 \parallel (788 + 50) = 313 \Omega$$

$$\therefore \frac{V_o}{V_i} = \frac{6.85}{26} \frac{1}{1 + \frac{6.85}{26} 45.5} 313 \frac{788}{838} \frac{3.3}{26} 147$$

$$\therefore a = 111$$

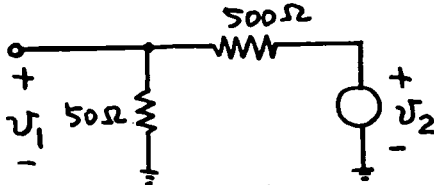
8-13

$$r_{ia} = r_{\pi 1} (1 + g_{m1} R_A)$$

$$= \frac{2600}{6.85} \left(1 + \frac{6.85}{26} 45.5 \right)$$

$$= 4.9 \text{ k}\Omega$$

$$r_{oa} = R_L = 147 \Omega$$



$$f = h_{12} f = \frac{v_1}{v_2} = \frac{1}{11}$$

$$\therefore \text{loop gain} = a f = \frac{1}{11} = 10.1$$

$$\therefore \text{with feedback loop closed,}$$

$$\text{gain} = \frac{v_o}{v_i} = \frac{a}{1 + a f} = \frac{111}{11.1} = 10.0$$

$$R_i = r_{ia} (1 + a f) = 4.9 \times 11.1 = 54 \text{ k}\Omega$$

$$R_o = \frac{r_{oa}}{1 + T} = \frac{147}{11.1} = 13.2 \Omega$$

For the full differential circuit

$$R_{id} = 2R_i = 108 \text{ k}\Omega$$

$$R_{od} = 2R_o = 26.4 \Omega$$

```

SERIES SHUNT FEEDBACK AMP
VCC 1 0 3V
VEE 2 0 -3V
RCL 1 9 500
RC2 1 10 500
Q1 9 3 5 NPN
Q2 10 4 6 NPN
RE1 5 7 50
RE2 6 7 50
RF1 11 5 500
RF2 12 6 500
Q3 11 9 8 NPN
Q4 12 10 8 NPN
RC3 1 11 200
RC4 1 12 200
REE1 7 2 78
REE2 8 2 280
.MODEL NPN NPN BF=100 IS=1E-14 RB=50
VII 3 0 0V
EVL1 0 4 3 0 1
.DC VII -0.1 0.1 0.005
.PLOT DC V(11,12)
.TF V(11,12) VII
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** DC TRANSFER CURVES

TNUM= 27.000 TEMP= 27.000

VOLT	V(11,12)					
(A)		-2.000E+00	-1.000E-00	0.	1.000E-00	2.000E+00
-1.000E-01	-1.16E+00	+	A	+	+	+
-9.500E-02	-1.14E+00	+	A	+	+	+
-9.000E-02	-1.13E+00	+	A	+	+	+
-8.500E-02	-1.11E+00	+	A	+	+	+
-8.000E-02	-1.10E+00	+	A	+	+	+
-7.500E-02	-1.08E+00	+	A	+	+	+
-7.000E-02	-1.07E+00	+	A	+	+	+
-6.500E-02	-1.05E+00	+	A	+	+	+
-6.000E-02	-1.04E+00	+	A	+	+	+
-5.500E-02	-1.01E+00	+	A	+	+	+
-5.000E-02	-9.58E-01	+	A	+	+	+
-4.500E-02	-8.77E-01	+	A	+	+	+
-4.000E-02	-7.87E-01	+	A	+	+	+
-3.500E-02	-6.93E-01	+	A	+	+	+
-3.000E-02	-5.96E-01	+	A	+	+	+
-2.500E-02	-4.98E-01	+	A	+	+	+
-2.000E-02	-3.99E-01	+	A	+	+	+
-1.500E-02	-3.00E-01	+	A	+	+	+
-1.000E-02	-2.00E-01	+	A	+	+	+
-5.000E-03	-1.00E-01	+	A	+	+	+
0.	0.	+	A	+	+	+
5.000E-03	1.00E-01	+	A	+	+	+
1.000E-02	2.00E-01	+	A	+	+	+
1.500E-02	3.00E-01	+	A	+	+	+
2.000E-02	3.99E-01	+	A	+	+	+
2.500E-02	4.98E-01	+	A	+	+	+
3.000E-02	5.96E-01	+	A	+	+	+
3.500E-02	6.93E-01	+	A	+	+	+
4.000E-02	7.87E-01	+	A	+	+	+
4.500E-02	8.77E-01	+	A	+	+	+
5.000E-02	9.58E-01	+	A	+	+	+
5.500E-02	1.01E+00	+	A	+	+	+
6.000E-02	1.04E+00	+	A	+	+	+
6.500E-02	1.05E+00	+	A	+	+	+
7.000E-02	1.07E+00	+	A	+	+	+
7.500E-02	1.08E+00	+	A	+	+	+
8.000E-02	1.10E+00	+	A	+	+	+
8.500E-02	1.11E+00	+	A	+	+	+
9.000E-02	1.13E+00	+	A	+	+	+
9.500E-02	1.14E+00	+	A	+	+	+
1.000E-01	1.16E+00	+	A	+	+	+

***** OPERATING POINT INFORMATION

TNUM= 27.000 TEMP= 27.000

+0:1	= 3.000E+00 0:2	= -3.000E+00 0:3	= 0.
+0:4	= 0. 0:5	= -7.078E-01 0:6	= -7.078E-01
+0:7	= -1.264E+00 0:8	= -1.073E+00 0:9	= -3.851E-01
+0:10	= -3.851E-01 0:11	= 1.454E+00 0:12	= 1.454E+00

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	Q:Q1	Q:Q2	Q:Q3	Q:Q4
MODEL	0:NPN	0:NPN	0:NPN	0:NPN
IB	6.739E-05	6.739E-05	3.406E-05	3.406E-05
IC	6.736E-03	6.736E-03	3.406E-03	3.406E-03
VBE	7.078E-01	7.078E-01	6.885E-01	6.885E-01
VCE	3.227E-01	3.227E-01	2.527E+00	2.527E+00
VBC	3.851E-01	3.851E-01	-1.839E+00	-1.839E+00
VS	3.851E-01	3.851E-01	-1.454E+00	-1.454E+00
POWER	2.222E-03	2.222E-03	8.633E-03	8.633E-03
BETAD	9.996E+01	9.996E+01	1.000E+02	1.000E+02
GM	2.604E-01	2.604E-01	1.317E-01	1.317E-01
RPI	3.839E+02	3.839E+02	7.593E+02	7.593E+02

8-14

```

RX      5.000E+01  5.000E+01  5.000E+01  5.000E+01
RO      1.008E+06  1.008E+06  1.840E+14  1.840E+14
CPI     0.         0.         0.         0.
CMU     0.         0.         0.         0.
CHK     0.         0.         0.         0.
CCS     0.         0.         0.         0.
BETAAC  9.999E+01  9.999E+01  9.999E+01  9.999E+01
FT      4.145E+13  4.145E+13  2.095E+13  2.095E+13

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(11,12)/VII = 2.002E+01
INPUT RESISTANCE AT VII = 5.154E+04
OUTPUT RESISTANCE AT V(11,12) = 2.630E+01

```

VII IS ONLY HALF OF TOTAL VI. VO/VI=20/2=10.
VII IS ONLY HALF OF TOTAL VI. RIN=2*5.154E+04=1.0308E+5.

SERIES SHUNT FEEDBACK AMP

```

VCC 1 0 3V
VBE 2 0 -3V
RCL 1 9 500 TC=1E-3
RC2 1 10 500 TC=1E-3
Q1 9 3 5 NPN
Q2 10 4 6 NPN
RE1 5 7 50 TC=1E-3
RE2 6 7 50 TC=1E-3
RF1 11 5 500 TC=1E-3
RF2 12 6 500 TC=1E-3
Q3 11 9 8 NPN
Q4 12 10 8 NPN
RC3 1 11 200 TC=1E-3
RC4 1 12 200 TC=1E-3
REK1 7 2 78 TC=1E-3
REK2 8 2 280 TC=1E-3
.MODEL NPN NPN BF=100 IS=1E-14 RB=50
VII 3 0 0V
EVAL 0 4 3 0 1
.TP V(11,12) VII
.TEMP -55 -35 -15 5 25 45 65 85 105 125
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

TEMP=-55 DEGREE C

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= -55.000

```

+0:1 = 3.000E+00 0:2 = -3.000E+00 0:3 = 0.
+0:4 = 0. 0:5 = -8.361E-01 0:6 = -8.361E-01
+0:7 = -1.361E+00 0:8 = -8.659E-01 0:9 = -3.985E-02
+0:10 = -3.985E-02 0:11 = 1.364E+00 0:12 = 1.364E+00

```

**** BIPOLAR JUNCTION TRANSISTORS

```

ELEMENT 0:Q1 0:Q2 0:Q3 0:Q4
MODEL 0:NPN 0:NPN 0:NPN 0:NPN
IB 6.582E-05 6.582E-05 4.110E-05 4.110E-05
IC 6.582E-03 6.582E-03 4.110E-03 4.110E-03
VBE 8.361E-01 8.361E-01 8.260E-01 8.260E-01
VCE 7.962E-01 7.962E-01 2.230E+00 2.230E+00
VBC 3.985E-02 3.985E-02 -1.404E+00 -1.404E+00
VB 3.985E-02 3.985E-02 -1.364E+00 -1.364E+00
POWER 5.296E-03 5.296E-03 9.203E-03 9.203E-03
BETAD 9.999E+01 9.999E+01 1.000E+02 1.000E+02
GM 3.501E-01 3.501E-01 2.187E-01 2.187E-01
RPI 2.856E+02 2.856E+02 4.573E+02 4.573E+02
RX 5.000E+01 5.000E+01 5.000E+01 5.000E+01
RO 7.097E+18 7.097E+18 3.714E+21 3.714E+21
CPI 0. 0. 0. 0.
CMU 0. 0. 0. 0.
CHK 0. 0. 0. 0.
CCS 0. 0. 0. 0.
BETAAC 1.000E+02 9.999E+01 1.000E+02 1.000E+02
FT 5.572E+13 5.572E+13 3.480E+13 3.480E+13

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(11,12)/VII = 2.040E+01
INPUT RESISTANCE AT VII = 6.280E+04
OUTPUT RESISTANCE AT V(11,12) = 1.951E+01

```

TEMP=-35 DEGREE C

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(11,12)/VII = 2.032E+01

TEMP=-15 DEGREE C

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(11,12)/VII = 2.023E+01

TEMP=5 DEGREE C

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(11,12)/VII = 2.013E+01

TEMP=25 DEGREE C

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(11,12)/VII

= 2.003E+01

TRANSISTORS Q1 AND Q2 BEGIN TO GET INTO SATURATION

TEMP=45 DEGREE C

**** BIPOLAR JUNCTION TRANSISTORS

```

ELEMENT 0:Q1 0:Q2 0:Q3 0:Q4
MODEL 0:NPN 0:NPN 0:NPN 0:NPN
IB 7.018E-05 7.018E-05 3.267E-05 3.267E-05
IC 6.768E-03 6.768E-03 3.267E-03 3.267E-03
VBE 6.790E-01 6.790E-01 6.571E-01 6.571E-01
VCE 2.173E-01 2.173E-01 2.592E+00 2.592E+00
VBC 4.617E-01 4.617E-01 -1.935E+00 -1.935E+00
VB 4.617E-01 4.617E-01 -1.473E+00 -1.473E+00
POWER 1.518E-03 1.518E-03 8.492E-03 8.492E-03
BETAD 9.643E+01 9.643E+01 1.000E+02 1.000E+02
GM 2.470E-01 2.470E-01 1.192E-01 1.192E-01
RPI 4.047E+02 4.047E+02 8.391E+02 8.391E+02
RX 5.000E+01 5.000E+01 5.000E+01 5.000E+01
RO 1.118E+04 1.118E+04 1.434E+13 1.434E+13
CPI 0. 0. 0. 0.
CMU 0. 0. 0. 0.
CHK 0. 0. 0. 0.
CCS 0. 0. 0. 0.
BETAAC 9.996E+01 9.996E+01 9.999E+01 9.999E+01
FT 3.929E+13 3.929E+13 1.896E+13 1.896E+13

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(11,12)/VII = 1.963E+01

TEMP=65 DEGREE C

**** BIPOLAR JUNCTION TRANSISTORS

```

ELEMENT 0:Q1 0:Q2 0:Q3 0:Q4
MODEL 0:NPN 0:NPN 0:NPN 0:NPN
IB 1.342E-04 1.342E-04 3.174E-05 3.174E-05
IC 6.740E-03 6.740E-03 3.174E-03 3.174E-03
VBE 6.500E-01 6.500E-01 6.223E-01 6.223E-01
VCE 1.356E-01 1.356E-01 2.623E+00 2.623E+00
VBC 5.144E-01 5.144E-01 -2.000E+00 -2.000E+00
VB 5.144E-01 5.144E-01 -1.486E+00 -1.486E+00
POWER 1.001E-03 1.001E-03 8.345E-03 8.345E-03
BETAD 5.023E+01 5.023E+01 1.000E+02 1.000E+02
GM 2.335E-01 2.335E-01 1.089E-01 1.089E-01
RPI 4.241E+02 4.241E+02 9.181E+02 9.181E+02
RX 5.000E+01 5.000E+01 5.000E+01 5.000E+01
RO 4.451E+02 4.451E+02 1.126E+12 1.126E+12
CPI 0. 0. 0. 0.
CMU 0. 0. 0. 0.
CHK 0. 0. 0. 0.
CCS 0. 0. 0. 0.
BETAAC 9.904E+01 9.904E+01 9.999E+01 9.999E+01
FT 3.681E+13 3.681E+13 1.733E+13 1.733E+13

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(11,12)/VII = 1.369E+01

TEMP=85 DEGREE C

**** BIPOLAR JUNCTION TRANSISTORS

```

ELEMENT 0:Q1 0:Q2 0:Q3 0:Q4
MODEL 0:NPN 0:NPN 0:NPN 0:NPN
IB 2.861E-04 2.861E-04 3.165E-05 3.165E-05
IC 6.618E-03 6.618E-03 3.165E-03 3.165E-03
VBE 6.254E-01 6.254E-01 5.880E-01 5.880E-01
VCE 1.076E-01 1.076E-01 2.591E+00 2.591E+00
VBC 5.178E-01 5.178E-01 -2.003E+00 -2.003E+00
VB 5.178E-01 5.178E-01 -1.485E+00 -1.485E+00
POWER 8.912E-04 8.912E-04 8.222E-03 8.222E-03
BETAD 2.313E+01 2.313E+01 1.000E+02 1.000E+02
GM 2.214E-01 2.214E-01 1.026E-01 1.026E-01
RPI 4.377E+02 4.377E+02 9.749E+02 9.749E+02
RX 5.000E+01 5.000E+01 5.000E+01 5.000E+01
RO 1.431E+02 1.431E+02 1.131E+11 1.131E+11
CPI 0. 0. 0. 0.
CMU 0. 0. 0. 0.
CHK 0. 0. 0. 0.
CCS 0. 0. 0. 0.
BETAAC 9.694E+01 9.694E+01 9.999E+01 9.999E+01
FT 3.413E+13 3.413E+13 1.632E+13 1.632E+13

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(11,12)/VII = 6.436E+00

TEMP=105 DEGREE C

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(11,12)/VII = 2.461E+00

TEMP=125 DEGREE C

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(11,12)/VII = 1.740E-01

BEFORE Q1 AND Q2 BECOME SATURATED (-55 TO 25 DEG C),
THE CIRCUIT GAIN REMAINS NEARLY CONSTANT.
DGAIN/DTA=-0.1/20 DEG C=-0.005/DEG C
(1/GAIN)(DGAIN/DT)=(1/20)(-0.1/20)=-250 PPM/DEG C

8.16

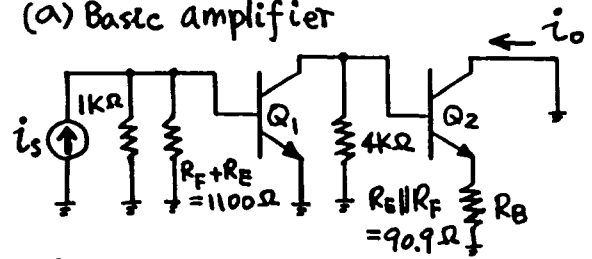
(a) T is almost independent of R_E .

This can be seen if the loop is broken and a signal inserted.

 R_F feeds current to the emitter of Q_1 and most of this is shunted into Q_1 .If $\underline{a}$ and $\underline{f}$ are calculated, $\underline{a}$ decreases as R_E increases and $\underline{f}$ increases by about the same percentage.(b) Loop gain is almost inversely proportional to R_F . As R_F increases, $\underline{f}$ decreases proportionately, whereas $\underline{a}$ changes slowly due to the 200Ω load resistor.(c) Loop gain is almost directly proportional to R_L since $\underline{a}$ depends on this quantity.

8.17

(a) Basic amplifier



Basic amplifier gain

$$\frac{i_o}{i_s} = - (1k \parallel 1.1k \parallel r_{\pi 1}) g_{m1} R_1 \frac{g_{m2}}{1 + g_{m2} R_B}$$

$$R_1 = 4k \parallel r_{\pi 2} (1 + g_{m2} R_B) \parallel r_{o1}$$

$$= 4k \parallel 5.2 \left(1 + \frac{90.9}{26}\right) k \parallel 100k$$

$$= 3.30 k\Omega$$

$$\therefore \frac{i_o}{i_s} = -476 \times \frac{3300}{26} \times \frac{1}{26} \times \frac{1}{4.5}$$

$$\therefore a = -516$$

$$Y_{ia} = 1k \parallel 1.1k \parallel r_{\pi 1} = 476 \Omega$$

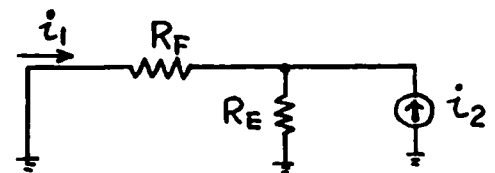
$$Y_{oa} = Y_{o2} \left(1 + g_{m2} R_B \frac{r_{\pi 2}}{r_{\pi 2} + R_{s2}}\right)$$

$$R_{s2} = r_{o1} \parallel 4k = 3.85 k\Omega$$

$$\therefore Y_{oa} = 100 \left(1 + \frac{90.9}{26} \frac{5.2}{5.2 + 3.85}\right) k$$

$$= 300 k\Omega$$

Feedback network



$$f = g_{12}f = \frac{i_1}{i_2} = -\frac{R_E}{R_E + R_F} = -\frac{100}{1100}$$

$$= -\frac{1}{11}$$

$$\therefore \text{loop gain} = \frac{516}{11} = 46.9 = af$$

$\therefore$ with feedback applied

$$\begin{aligned} \text{overall gain} &= \frac{i_o}{i_i} = \frac{a}{1+af} \\ &= \frac{-516}{47.9} = -10.8 \end{aligned}$$

Input resistance

$$R_i = \frac{r_{ia}}{1+T} = \frac{476}{47.9} = 9.94 \Omega$$

Output resistance

$$R_o = r_{oa}(1+T) = 300 \times 47.9 = 14.4 \text{ M}\Omega$$

(b) f is unchanged

a increases by about 10%

$\therefore$ change in overall gain is

$$\approx \frac{10}{47.9} = 0.2\%$$

R_i changes by -10% because

$$R_i = \frac{r_{ia}}{1+af}$$

8.18

(a) Basic amplifier gain

$$\frac{i_o}{i_s} = -\left[(R_F + R_E) \parallel r_{\pi 1}\right] g_{m1} R_1 \frac{g_{m2}}{1+g_{m2}R_B}$$

$$R_F + R_E = 5.2 \text{ k}\Omega$$

$$R_B = R_E \parallel R_F = 192 \Omega$$

$$\begin{aligned} R_1 &= R_{L1} \parallel r_{\pi 2}(1+g_{m2}R_B) \parallel r_{o1} \\ &= 10 \text{ k} \parallel 5.2 \left(1 + \frac{192}{26}\right) \text{ k} \parallel 100 \text{ k} \\ &= 7.52 \text{ k}\Omega \end{aligned}$$

$$\therefore \frac{i_o}{i_i} = -\left[5.2 \text{ k} \parallel 5.2 \text{ k}\right] \frac{7520}{26} \frac{1}{26} \frac{1}{8.38}$$

$$\therefore a = -3451$$

$$r_{ia} = 5.2 \text{ k} \parallel 5.2 \text{ k} = 2.6 \text{ k}\Omega$$

$$r_{oa} = r_{o2} \left(1 + g_{m2}R_B \frac{r_{\pi 2}}{r_{\pi 2} + R_{S2}}\right)$$

$$R_{S2} = r_{o1} \parallel 10 \text{ k} = 9.09 \text{ k}\Omega$$

$$\begin{aligned} \therefore r_{oa} &= 100 \left(1 + \frac{192}{26} \frac{5.2}{5.2 + 9.09}\right) \\ &= 369 \text{ k}\Omega \end{aligned}$$

Feedback network

$$\begin{aligned} f = g_{12}f &= \frac{i_1}{i_2} = -\frac{R_E}{R_E + R_F} \\ &= -\frac{200}{5200} = -0.0385 \end{aligned}$$

$$\begin{aligned} \therefore \text{loop gain} &= 3451 \times 0.0385 \\ &= 133 \end{aligned}$$

$\therefore$ With feedback applied

$$\begin{aligned} \text{overall gain} &= \frac{i_o}{i_i} = \frac{a}{1+af} \\ &= \frac{-3451}{134} = -25.8 \end{aligned}$$

Input resistance

$$R_i = \frac{2600}{134} = 19.4 \Omega$$

Output resistance

$$R_o = 369 \times 134 = 49.4 \text{ M}\Omega$$

(b) If I_{C1} increases 20%

g_{m1} increases 20%

$r_{\pi 1}$ decreases 20%

$\therefore a$ increases about 10%,

since $(R_F + R_E) = r_{\pi 1}$

f is unchanged

$\therefore$ Change in overall gain is

$$\frac{10}{1+T} = \frac{10}{134} = 0.075\%$$

$$R_o = r_{oa}(1+af)$$

$\therefore R_o$ increases about 10%

8.19

Transconductance

$$G_m = \frac{1}{R_E} \frac{1}{1 + \frac{1}{R_E} \left(\frac{1}{g_m} + \frac{r_b + R_E}{\beta_o} \right)}$$

$$= \frac{1}{200} \frac{1}{1 + \frac{1}{200} \left(26 + \frac{400}{150} \right)}$$

$$= 4.37 \text{ mA/V}$$

Input resistance

$$R_i = r_b + r_\pi + (1 + \beta_o) R_E$$

$$= 200 + 150 \times 26 + 151 \times 200$$

$$= 34.3 \text{ k}\Omega$$

Output resistance

$$R_o = r_o \left(1 + \frac{g_m R_E}{1 + \frac{r_b + R_E}{r_\pi}} \right)$$

$$= 80 \left(1 + \frac{\frac{200}{26}}{1 + \frac{400}{150 \times 26}} \right)$$

$$= 638 \text{ k}\Omega$$

$$\text{Loop gain } T = \frac{g_m R_E}{1 + \frac{r_b + R_E}{r_\pi}}$$

$$= 7$$

8.20

(a) Assume high β

$$I_{Q8} = \frac{12 - 0.6}{11.4} = 1 \text{ mA}$$

$$\therefore I_{Q7} \approx \frac{1400}{300} \times 1 = 4.7 \text{ mA}$$

$$\therefore I_{Q1} = I_{Q2} = \frac{1}{2} \times 4.7 = 2.3 \text{ mA}$$

$$I_{Q9} = 4.7 \text{ mA}$$

$$\therefore I_{Q3} = I_{Q4} = 2.3 \text{ mA}$$

$$I_{Q10} = I_{Q11} = \frac{1400}{400} \times 1 = 3.5 \text{ mA}$$

$$V_{C3} = V_{C4} = 6 - 1.1 \times 2.3 = 3.5 \text{ V}$$

 $\therefore$ DC output voltage

$$= 3.5 - 0.6 = 2.9 \text{ V}$$

Sum currents at collector of Q_1

$$I_{Q1} = \frac{6 - V_{C1}}{2.4} + \frac{2.9 - V_{C1}}{7}$$

$$\therefore 2.3 = 2.5 - 0.42 V_{C1} + 0.41 - 0.14 V_{C1}$$

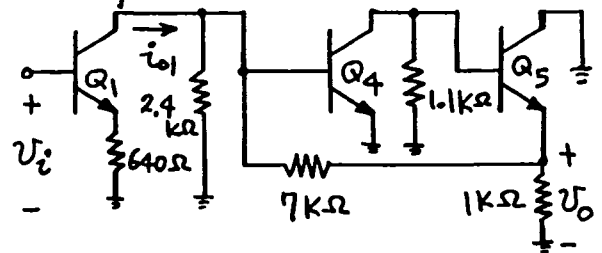
$$\therefore V_{C1} = 1 \text{ V}$$

 $\therefore$ Current in $7 \text{ k}\Omega$ resistor

$$= \frac{2.9 - 1}{7} = 0.27 \text{ mA}$$

$$\therefore I_{Q5} = I_{Q6} = I_{Q10} + 0.27 = 3.8 \text{ mA}$$

(b) Half-circuit



$$R_i = r_{\pi 1} + (1 + \beta) R_{E1}$$

$$= \frac{100 \times 26}{2.3} + 101 \times 640 = 66 \text{ k}\Omega$$

— for the half circuit

$$\therefore R_i = 132 \text{ k}\Omega \text{ — for the complete circuit}$$

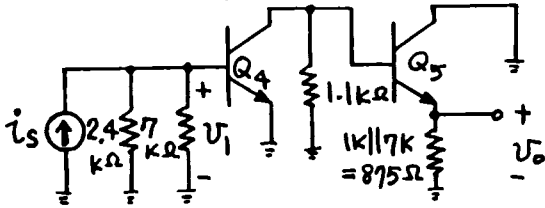
For the first stage

$$\frac{i_{o1}}{v_i} = - \frac{1}{640} \frac{1}{1 + \frac{1}{600} \left(\frac{26}{2.3} + \frac{640}{100} \right)}$$

$$= -1.52 \text{ mA/V}$$

Consider the shunt-shunt feedback stage.

Basic amplifier is



$$V_i = i_s(2.4k \parallel 7k \parallel r_{\pi 4})$$

$$= i_s \times 0.69k$$

$$R_{i5} = r_{\pi 5} + (1 + \beta) \times 875$$

$$= 684 + 88.4k = 89k \Omega$$

$$\therefore \frac{v_o}{i_s} = -0.69k \times g_{m4} [1.1k \parallel 89k]$$

$$= -0.69k \times \frac{2.3}{26} \times 1087$$

$$\therefore a = -66.3k \Omega$$

$$f = -\frac{1}{7k}$$

$\therefore$ For the output stage with feedback applied

$$\frac{v_o}{i_{o1}} = \frac{a}{1 + af} = \frac{-281k}{1 + 9.47} = -6.33k \Omega$$

$\therefore$ for the overall circuit

$$\frac{v_o}{v_i} = 1.52 \times 10^{-3} \times 6.33 \times 10^3 = 9.6$$

Loop gain of output stage

$$T = af = 9.47$$

Output impedance of half circuit

$$= 875 \parallel \left[\frac{1}{g_{m5}} + \frac{1100}{\beta} \right]$$

$$= 875 \parallel [7 + 11] = 18 \Omega$$

$\therefore$ For the complete circuit

$$R_{oa} = 36 \Omega, \text{ and with feedback applied, } R_o = \frac{36}{1 + T} = 3.6 \Omega$$

```

733 AMP
VCC 1 0 6V
VEE 2 0 -6V
RCL 1 5 2.4K
RC2 1 6 2.4K
Q1 5 3 7 NPN
Q2 6 4 8 NPN
RE1 7 16 640
RE2 8 16 640
Q3 9 6 15 NPN
Q4 10 5 15 NPN
RC3 1 9 1.1K
RC4 1 10 1.1K
Q5 1 10 11 NPN
Q6 1 9 12 NPN
RF1 11 5 7K
RF2 12 6 7K
RL 11 12 2K
Q7 16 17 18 NPN
Q8 17 17 19 NPN
Q9 15 17 20 NPN
Q10 11 17 13 NPN
Q11 12 17 14 NPN
RQ7 18 2 300
RQ8 19 2 1.4K
RQ9 20 2 300
RQ10 13 2 400
RQ11 14 2 400
RBIAS 1 17 10K
.MODEL NPN NPN BF=100 IS=1E-13
V11 3 0 0V
V12 4 0 0V
.TF V(11,12) V11
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

```

***** OPERATING POINT INFORMATION          TWCN= 27.000 TEMP= 27.000
+0:1      = 6.000E+00 0:2      = -6.000E+00 0:3      = 0.
+0:4      = 0.          0:5      = 1.767E+00 0:6      = 1.767E+00
+0:7      = -6.128E-01 0:8      = -6.128E-01 0:9      = 3.822E+00
+0:10     = 3.822E+00 0:11     = 3.197E+00 0:12     = 3.197E+00
+0:13     = -4.800E+00 0:14     = -4.800E+00 0:15     = 1.155E+00
+0:16     = -1.872E+00 0:17     = -4.176E+00 0:18     = -4.807E+00
+0:19     = -4.768E+00 0:20     = -4.807E+00

```

```

**** BIPOLAR JUNCTION TRANSISTORS
ELEMENT 0:Q1 0:Q2 0:Q3 0:Q4 0:Q5 0:Q6
MODEL 0:NPN 0:NPN 0:NPN 0:NPN 0:NPN 0:NPN
IB 1.948E-05 1.948E-05 1.948E-05 1.948E-05 3.142E-05 3.142E-05
IC 1.948E-03 1.948E-03 1.948E-03 1.948E-03 3.142E-03 3.142E-03
VBE 6.128E-01 6.128E-01 6.128E-01 6.128E-01 6.252E-01 6.252E-01
VCE 2.380E+00 2.380E+00 2.667E+00 2.667E+00 2.802E+00 2.802E+00
VBC -1.767E+00 -1.767E+00 -2.054E+00 -2.054E+00 -2.177E+00 -2.177E+00
VS -1.767E+00 -1.767E+00 -3.822E+00 -3.822E+00 -6.000E+00 -6.000E+00
POWER 4.650E-03 4.650E-03 5.209E-03 5.209E-03 8.826E-03 8.826E-03
BETAD 1.000E+02 1.000E+02 1.000E+02 1.000E+02 1.000E+02 1.000E+02
GM 7.532E-02 7.532E-02 7.532E-02 7.532E-02 1.215E-01 1.215E-01
RPI 1.327E+03 1.327E+03 1.327E+03 1.327E+03 8.231E+02 8.231E+02
RX 0. 0. 0. 0. 0. 0.
RO 1.767E+13 1.767E+13 2.054E+13 2.054E+13 2.177E+13 2.177E+13
BETAAC 9.999E+01 9.999E+01 9.999E+01 9.999E+01 9.999E+01 9.999E+01
FT 1.198E+13 1.198E+13 1.198E+13 1.198E+13 1.933E+13 1.933E+13
ELEMENT 0:Q7 0:Q8 0:Q9 0:Q10 0:Q11
MODEL 0:NPN 0:NPN 0:NPN 0:NPN 0:NPN
IB 3.935E-05 8.709E-06 3.935E-05 2.969E-05 2.969E-05
IC 3.935E-03 8.709E-04 3.935E-03 2.969E-03 2.969E-03
VBE 6.310E-01 5.920E-01 6.310E-01 6.237E-01 6.237E-01
VCE 2.935E+00 5.920E-01 5.962E+00 7.997E+00 7.997E+00
VBC -2.304E+00 0. -5.331E+00 -7.373E+00 -7.373E+00
VS 1.872E+00 4.176E+00 -1.155E+00 -3.197E+00 -3.197E+00
POWER 1.158E-02 5.207E-04 2.349E-02 2.377E-02 2.377E-02
BETAD 1.000E+02 1.000E+02 1.000E+02 1.000E+02 1.000E+02
GM 1.522E-01 3.367E-02 1.522E-01 1.148E-01 1.148E-01
RPI 6.572E+02 2.970E+03 6.572E+02 8.710E+02 8.710E+02
RX 0. 0. 0. 0. 0.
RO 2.304E+13 2.586E+11 5.331E+13 7.373E+13 7.373E+13
BETAAC 9.999E+01 9.999E+01 9.999E+01 9.999E+01 9.999E+01
FT 2.421E+13 5.358E+12 2.421E+13 1.827E+13 1.827E+13

```

HAND ANALYSIS STARTS WITH BIAS STRING: Q8 AND RESISTORS OF 10K AND 1.4K AND FIND IC8=1mA. BUT IT FAILS TO ACCOUNT FOR BASE CURRENTS OF Q7, Q9, Q10, Q11.

USING SPICE, WE SEE THAT THIS 1mA IS DIVIDED AMONG THESE TRANSISTORS: 1mA=IC8+IB7+IB9+IB10+IB11

SO THE SPICE DC BIAS CURRENTS OF TRANSISTORS ARE DIFFERENT FROM THE VALUES OBTAINED BY HAND.

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(11,12)/V11      = 9.531E+00
INPUT RESISTANCE AT V11      = 1.319E+05
OUTPUT RESISTANCE AT V(11,12) = 3.793E+00

```


8.21

Output resistance before loop is closed, $r_{oa} = 93 \Omega$

Regulator amplifier gain

$$a = 3054$$

$$V_o = V_R \frac{R_1 + R_2}{R_2}$$

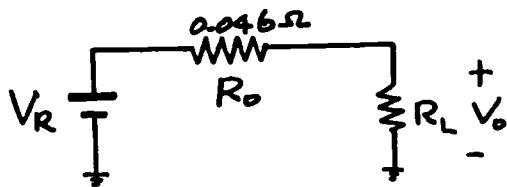
$$\therefore \frac{R_1 + R_2}{R_2} = \frac{V_o}{V_R} = \frac{10}{6.8} = 1.5$$

$$\therefore T = a \frac{R_2}{R_1 + R_2} = \frac{3054}{1.5} = 2036$$

$$\text{Output resistance} = \frac{r_{oa}}{1 + T}$$

$$= \frac{93}{2037}$$

$$\therefore R_o = 0.046 \Omega$$



$$V_o = \frac{R_L}{R_L + R_o} V_R$$

$$R_L = 1k\Omega$$

$$10 = \frac{1000}{1000.046} V_R$$

$$\therefore V_R = 10.00046 \text{ V}$$

$$R_L = 500 \Omega$$

$$V_o = \frac{500}{500.046} \times 10.00046$$

$$= 9.9995 \text{ V}$$

723 VOLTAGE REGULATOR

* VR VOLTAGE REFERENCE GENERATOR

VCC 1 0 15V
 D1 2 1 DIODE
 IBIAS 2 0 1MA
 R1 1 3 500
 Q2 4 4 3 P
 R2 4 2 15.5K
 Q3 6 4 5 P
 R3 1 5 25K
 Q6 6 7 0 N
 C1 6 7 5PF
 Q4 1 6 11 N
 Q5 1 11 10 N
 R6 10 9 100
 D2 8 9 DIODE
 R7 7 8 30K
 R8 8 0 5K
 * VOLTAGE AMPLIFIER
 RC 9 18 667
 R4 1 12 1K
 Q7 13 4 12 P
 Q10 13 14 15 N
 R9 15 0 300
 R10 14 0 20K
 Q9 1 13 14 N
 Q11 1 18 17 N
 Q8 19 4 20 P
 R5 1 20 1K
 Q12 19 21 17 N
 C2 19 21 100PF
 Q13 17 14 16 N
 R11 16 0 150
 Q14 1 19 22 N
 R12 22 23 15K
 Q15 1 22 23 N
 * (RA+RB)/RB = VO/VR = 10/6.8 = 1.5 = 3/2
 * CHOOSE RA = 1K, RB = 2K
 RA 23 21 1K
 RB 21 0 2K
 RLOAD 23 0 1K
 .MODEL N NPN BF=100 VAF=100 IS=1E-15
 .MODEL P PNP BF=100 VAF=100 IS=1E-15
 .MODEL DIODE D BV=6.2 IS=1E-15
 .TF V(23) VCC
 .OPTIONS NOPAGE NOMOD
 .WIDTH OUT=80
 .OPTIONS SPICE
 .OP
 .END

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

+0:1	= 1.500E+01 0:2	= 8.810E+00 0:3	= 1.483E+01
+0:4	= 1.414E+01 0:5	= 1.473E+01 0:6	= 7.949E+00
+0:7	= 5.946E-01 0:8	= 5.975E-01 0:9	= 6.742E+00
+0:10	= 6.754E+00 0:11	= 7.412E+00 0:12	= 1.481E+01
+0:13	= 1.356E+00 0:14	= 7.276E-01 0:15	= 5.653E-02
+0:16	= 4.543E-02 0:17	= 6.085E+00 0:18	= 6.741E+00
+0:19	= 1.158E+01 0:20	= 1.481E+01 0:21	= 6.754E+00
+0:22	= 1.091E+01 0:23	= 1.013E+01	

**** DIODES

ELEMENT	0:D1	0:D2
MODEL	0:DIODE	0:DIODE
ID	-6.560E-04	-1.196E-04
VD	-6.189E+00	-6.145E+00
REQ	3.942E+01	2.162E+02
CAP	0.	0.

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	0:Q2	0:Q3	0:Q6	0:Q4	0:Q5	0:Q7
MODEL	0:P	0:P	0:N	0:N	0:N	0:P
IB	-3.371E-06	-9.770E-08	9.655E-08	1.028E-08	1.111E-06	-1.657E-06
IC	-3.371E-04	-1.038E-05	1.036E-05	1.101E-06	1.195E-04	-1.869E-04
VBE	-6.865E-01	-5.949E-01	5.946E-01	5.367E-01	6.578E-01	-6.682E-01
VCE	-6.865E-01	-6.789E+00	7.949E+00	7.587E+00	8.245E+00	-1.345E+01
VBC	0.	6.194E+00	-7.354E+00	-7.050E+00	-7.587E+00	1.278E+01
VS	-1.414E+01	-1.414E+01	-7.949E+00	-1.500E+01	-1.500E+01	-1.414E+01
POWER	2.337E-04	7.049E-05	8.245E-05	8.358E-06	9.864E-04	2.516E-03
BETAD	1.000E+02	1.061E+02	1.073E+02	1.070E+02	1.075E+02	1.127E+02
GM	1.303E-02	4.010E-04	4.006E-04	4.255E-05	4.621E-03	7.226E-03
RPI	7.672E+03	2.647E+05	2.678E+05	2.515E+06	2.327E+04	1.560E+04
RX	0.	0.	0.	0.	0.	0.
RO	2.966E+05	1.023E+07	1.035E+07	9.724E+07	8.999E+05	6.033E+05
CPI	0.	0.	0.	0.	0.	0.
CMU	0.	0.	0.	0.	0.	0.
CEX	0.	0.	0.	0.	0.	0.
CCS	0.	0.	0.	0.	0.	0.
BETAAC	9.997E+01	1.061E+02	1.073E+02	1.070E+02	1.075E+02	1.127E+02
FT	2.073E+12	6.382E+10	6.376E+10	6.772E+09	7.354E+11	1.150E+12

ELEMENT	0:Q10	0:Q9	0:Q11	0:Q8	0:Q12	0:Q13
MODEL	0:N	0:N	0:N	0:P	0:N	0:N
IB	1.854E-06	3.583E-07	1.056E-06	-1.800E-06	1.745E-06	2.848E-06
IC	1.866E-04	4.072E-05	1.143E-04	-1.847E-04	1.829E-04	3.000E-04

VBE	6.711E-01	6.286E-01	6.565E-01	-6.703E-01	6.695E-01	6.822E-01
VCE	1.299E+00	1.427E+01	8.914E+00	-3.229E+00	5.498E+00	6.040E+00
VBC	-6.286E-01	-1.364E+01	-8.258E+00	2.559E+00	-4.829E+00	-5.357E+00
VS	-1.356E+00	-1.500E+01	-1.500E+01	-1.414E+01	-1.158E+01	-6.085E+00
POWER	2.437E-04	5.814E-04	1.020E-03	5.976E-04	1.007E-03	1.814E-03
BETAD	1.006E+02	1.136E+02	1.082E+02	1.025E+02	1.048E+02	1.053E+02
GM	7.212E-03	1.574E-03	4.418E-03	7.138E-03	7.071E-03	1.160E-02
RPI	1.394E+04	7.217E+04	2.449E+04	1.436E+04	1.482E+04	9.082E+03
RX	0.	0.	0.	0.	0.	0.
RO	5.393E+05	2.790E+06	9.471E+05	5.554E+05	5.730E+05	3.511E+05
CPI	0.	0.	0.	0.	0.	0.
CMU	0.	0.	0.	0.	0.	0.
CEX	0.	0.	0.	0.	0.	0.
CCS	0.	0.	0.	0.	0.	0.
BETAAC	1.006E+02	1.136E+02	1.082E+02	1.025E+02	1.048E+02	1.053E+02
FT	1.147E+12	2.505E+11	7.031E+11	1.136E+12	1.125E+12	1.845E+12

ELEMENT	0:Q14	0:Q15
MODEL	0:N	0:N
IB	1.725E-06	1.281E-04
IC	1.784E-04	1.333E-02
VBE	6.692E-01	7.806E-01
VCE	4.085E+00	4.865E+00
VBC	-3.416E+00	-4.085E+00
VS	-1.500E+01	-1.500E+01
POWER	7.300E-04	6.498E-02
BETAD	1.034E+02	1.040E+02
GM	6.896E-03	5.154E-01
RPI	1.499E+04	2.019E+02
RX	0.	0.
RO	5.796E+05	7.806E+03
CPI	0.	0.
CMU	0.	0.
CEX	0.	0.
CCS	0.	0.
BETAAC	1.033E+02	1.040E+02
FT	1.097E+12	8.202E+13

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(23)/VCC	=	4.207E-04
INPUT RESISTANCE AT VCC	=	8.035E+05
OUTPUT RESISTANCE AT V(23)	=	5.444E-02

LOAD REGULATION:

(DVO/VO)/DIO=(DVO/DIO)/VO=RO/VO=5.444E-2/10=5.4E-3

LINE REGULATION:

(DVO/VO)/DVCC=(DVO/DVCC)/VO=4.207E-4/10=4.3E-5

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$$V_{CC} = I_{D2} 10k + V_{BE2} + V_{GS2}$$

$$5 = I_{D2} 10k + 0.8 + V_{GS2}$$

$$= \frac{40\mu}{2} 30 (V_{GS2} - 0.8)^2 10k + 0.8 + V_{GS2}$$

$$= 6(V_{GS2} - 0.8)^2 + 0.8 + V_{GS2}$$

$$0 = 6V_{GS2}^2 - 8.6V_{GS2} - 0.36$$

$$V_{GS2} = \frac{8.6 \pm \sqrt{8.6^2 - 4(6)(-0.36)}}{12}$$

$$= \frac{8.6 \pm 9.088}{12}$$

$$V_{GS2} = 1.47V$$

$$I_{D2} = \frac{40\mu}{2} 30 (1.47 - 0.8)^2 = 273\mu A$$

$$V_{BQ2} = 5 - I_{D2} 10k = 2.27V$$

$$V_{EQ2} = V_{BQ2} - 0.8 = 1.47V$$

$$I_{RL1} = \frac{5 - 1.47}{1k} = 3.53mA$$

$$I_{D1} = 3.53mA + \frac{5 - (V_{GS1} + 0.8)}{10k}$$

$$10k I_{D1} = 35.3 + 5 - V_{GS1} - 0.8$$

$$= 39.5 - V_{GS1}$$

$$10k \frac{40\mu}{2} 300 (V_{GS1} - 0.8)^2 = 39.5 - V_{GS1}$$

$$60 (V_{GS1} - 0.8)^2 = 39.5 - V_{GS1}$$

$$60 V_{GS1}^2 - 95 V_{GS1} - 1.1 = 0$$

$$V_{GS1} = \frac{95 \pm \sqrt{95^2 - 4(60)(-1.1)}}{120}$$

$$= \frac{95 \pm 96.4}{120}$$

$$V_{GS1} = 1.59V$$

$$I_{D1} = 3.53mA + \frac{5 - (1.59 + 0.8)}{10k}$$

$$= 3.53mA + I_{CQ1}$$

$$= 3.53mA + 0.26mA$$

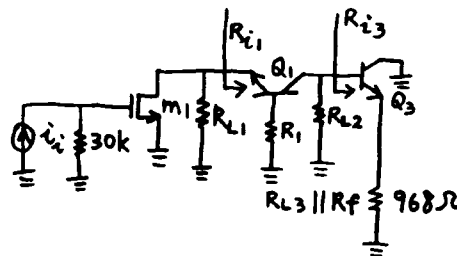
$$= 3.79mA$$

8-21

$$I_{CQ1} = 0.26mA$$

$$I_{C3} = \frac{1.59V}{1k} = 1.59mA$$

forward path



$$R_{i1} = \frac{1}{g_{mQ1}} + \frac{R_1}{\beta}$$

$$= \frac{26mV}{0.26mA} + \frac{1174}{100}$$

$$= 112$$

$$R_1 = 10k \parallel \left(\frac{1}{g_{mQ2}} + \frac{1}{g_{mM2}} \right)$$

$$= 10k \parallel \left(\frac{26mV}{273\mu A} + \frac{1}{\sqrt{2(40\mu)(30)(273\mu)}} \right)$$

$$= 10k \parallel (95.2 + 1.24k)$$

$$= 1174$$

$$R_{i3} = r_{\pi3} (1 + g_{m3} R_{E3})$$

$$= \frac{100}{g_{m3}} (1 + g_{m3} 968)$$

$$= 98.4k$$

$$\frac{V_o}{i_i} = -30k g_{mM1} \frac{R_{L1}}{R_{L1} + R_{i1}} (R_{L2} \parallel R_{i3}) A_{V3}$$

$$= -30k (9.54mA/V) \left(\frac{1000}{1112} \right) (9.08k) (0.983)$$

$$= -2.3M\Omega = a$$

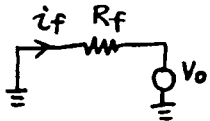
$$g_{mM1} = \sqrt{2(40\mu)(300)(3.79mA)}$$

$$= 9.54mA/V$$

$$A_{V3} = \frac{g_{m3} 968}{1 + g_{m3} 968} = 0.983$$

$$R_{L2} \parallel R_{i3} = 10k \parallel 98.4k \\ = 9.08k$$

feedback



$$V_o f = i_f$$

$$f = \frac{-1}{R_f} = \frac{-1}{30k}$$

$$T = af = 76.7$$

$$R_{in} = \frac{30k}{1+76.7} = 386\Omega$$

$$R_{out} = \frac{r_{out}}{1+76.7} \\ = \frac{104}{77.7} = 1.34\Omega$$

$$R_{out} = 968 \parallel \left(\frac{1}{\beta m_3} + \frac{R_{L2}}{\beta} \right) \\ = 104$$

$$A = \frac{a}{1+T} = \frac{-2.3M}{1+76.7} = -29.6k\Omega = \frac{V_o}{i_i}$$

```

BICMOS AMP
VCC 1 0 5V
RL1 1 4 1K
M1 4 2 0 0 NMOS W=300U L=1U
II 2 0 0A
RF 2 7 30K
RE 7 0 1K
RL2 1 3 10K
REBIAS 1 5 10K
Q1 3 5 4 NPN
Q2 5 5 6 NPN
Q3 1 3 7 NPN
M2 6 6 0 0 NMOS W=300U L=1U
.DC II -0.1M 0.1M 0.01M
.PLOT DC V(7)
.TF V(7) II
.MODEL NMOS NMOS KP=40U LAMBDA=0 VTO=0.8
.MODEL NPN NPN IS=1E-16 BF=100 RB=0
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
*****
***** DC TRANSFER CURVES THOM= 27.000 TEMP= 27.000
      AMPS      V(7)
      (A)      0.      1.000E+00      2.000E+00      3.000E+00      4.000E+00
-1.000E-04      1.00E-01 +-----+-----+-----+-----+
-9.000E-05      9.00E-02 +A + + + + + + + + + +
-8.000E-05      8.00E-02 +A + + + + + + + + + +
-7.000E-05      7.00E-02 +A + + + + + + + + + +
-6.000E-05      6.01E-02 +A + + + + + + + + + +
-5.000E-05      1.97E-01 + A + + + + + + + + + +
-4.000E-05      4.57E-01 + A+ + + + + + + + + +
-3.000E-05      7.16E-01 + + A + + + + + + + + + +
-2.000E-05      1.00E+00 + + A + + + + + + + + + +
-1.000E-05      1.29E+00 + + + A + + + + + + + + + +
0.      1.59E+00 +-----+-----+-----+-----+
1.000E-05      1.88E+00 + + + + A + + + + + + + + + +
2.000E-05      2.18E+00 + + + + + A + + + + + + + + + +
3.000E-05      2.48E+00 + + + + + + A + + + + + + + + + +
4.000E-05      2.77E+00 + + + + + + + A + + + + + + + + + +
5.000E-05      3.07E+00 + + + + + + + + A + + + + + + + + + +
6.000E-05      3.36E+00 + + + + + + + + + A + + + + + + + + + +
7.000E-05      3.66E+00 + + + + + + + + + + A + + + + + + + + + +
8.000E-05      3.80E+00 + + + + + + + + + + + A + + + + + + + + + +
9.000E-05      3.80E+00 + + + + + + + + + + + + A + + + + + + + + + +
1.000E-04      3.80E+00 +-----+-----+-----+-----+
***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000
+0:1      = 5.000E+00 0:2      = 1.592E+00 0:3      = 2.378E+00
+0:4      = 1.480E+00 0:5      = 2.218E+00 0:6      = 1.477E+00
+0:7      = 1.592E+00
**** BIPOLAR JUNCTION TRANSISTORS
ELEMENT 0:Q1      0:Q2      0:Q3
MODEL    0:NPN      0:NPN      0:NPN
IB       2.464E-06      2.730E-06      1.577E-05
IC       2.464E-04      2.730E-04      1.577E-03
VBE      7.380E-01      7.406E-01      7.860E-01
VCE      8.980E-01      7.406E-01      3.407E+00
VBC      -1.600E-01      0.      -2.621E+00
VS       -2.378E+00      -2.218E+00      -5.000E+00
POWER    2.231E-04      2.042E-04      5.385E-03
BETAD    1.000E+02      1.000E+02      1.000E+02
GM       9.526E-03      1.055E-02      6.096E-02
RPI      1.049E+04      9.475E+03      1.640E+03
RX       0.      0.      0.
RO       1.257E+17      2.586E+14      2.621E+16
BETAAC   9.999E+01      9.999E+01      9.999E+01
FT       1.516E+12      1.679E+12      9.702E+12
**** MOSFETS
ELEMENT 0:M1      0:M2
MODEL    0:NMOS      0:NMOS
ID       3.768E-03      2.757E-04
IBS      0.      0.
IBD      -1.480E-14      -1.478E-14
VGS      1.592E+00      1.477E+00
VDS      1.480E+00      1.477E+00
VBS      0.      0.
VTH      8.000E-01      8.000E-01
VDSAT    7.925E-01      6.779E-01
BETA     1.200E-02      1.200E-03
GAM EFF  0.      0.
GM       9.510E-03      8.134E-04
**** SMALL-SIGNAL TRANSFER CHARACTERISTICS
V(7)/II      = 2.960E+04
INPUT RESISTANCE AT      II      = 3.925E+02
OUTPUT RESISTANCE AT V(7)      = 1.347E+00

```

8.23

$$\frac{V_{DD} - V_{GS2}}{10k} = I_{D2} = \frac{30\mu}{2} 20(V_{GS2} - 0.8)^2$$

$$5 - a = 3(a - 0.8)^2$$

$$= 3a^2 - 4.8a + 1.92$$

$$0 = 3a^2 - 3.8a - 3.08$$

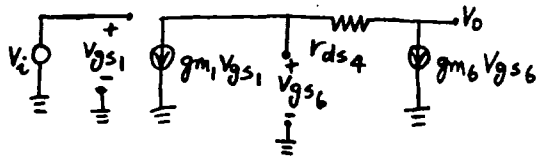
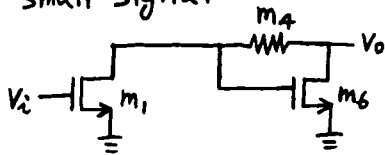
$$a = \frac{+3.8 \pm \sqrt{3.8^2 - 4(3)(-3.08)}}{6}$$

$$V_{GS2} = 1.83V$$

$$I_{D2} = \frac{30\mu}{2} 20(1.83 - 0.8)^2$$

$$= 317\mu A = I_{D1} = I_{D5} = I_{D6}$$

small signal



$$V_o = V_{GS6} - g_{m6} V_{GS6} r_{ds4}$$

$$g_{m1} = g_{m6}$$

$$-g_{m1} V_{GS1} = g_{m6} V_{GS6}$$

$$-V_{GS1} = V_{GS6} = -V_i$$

$$V_o = -V_i + g_{m6} V_i r_{ds4}$$

$$\frac{V_o}{V_i} = -1 + g_{m6} r_{ds4}$$

$$g_{m6} = \sqrt{2(317\mu)(60\mu)(20)}$$

$$= 872 \mu A/V$$

$$g_{ds4} = \mu_n C_{ox} \frac{W}{L} (V_{GS4} - V_{t4})$$

$$= 150\mu (V_c - 1.53 - 1.14)$$

$$= 150\mu (V_c - 2.67)$$

8-23

$$V_{t4} = V_{t0} + \gamma(\sqrt{V_{SB4} + 2\phi_f} - \sqrt{2\phi_f})$$

$$= 0.8 + 0.5(\sqrt{1.53 + 0.6} - \sqrt{0.6})$$

$$= 1.14V$$

$$V_{SB4} = V_{GS6} = V_{t6} + \sqrt{\frac{2I_{D6}}{\mu C_{ox} \frac{W}{L}_6}}$$

$$= 0.8 + \sqrt{\frac{2(317\mu)}{60\mu(20)}}$$

$$= 1.53V$$

$$V_c = 3V$$

$$g_{ds4} = 150\mu(3 - 2.67)$$

$$= 49.5\mu$$

$$r_{ds4} = 20.2k$$

$$\frac{V_o}{V_i} = -1 + (872\mu)(20.2k)$$

$$= 16.6$$

$$V_c = 4V$$

$$g_{ds4} = 150\mu(4 - 2.67)$$

$$= 200\mu$$

$$r_{ds4} = 5.01k$$

$$\frac{V_o}{V_i} = -1 + (872\mu)(5.01k)$$

$$= 3.37$$

$$R_o = \frac{1}{g_{m6}} = \frac{1}{872\mu} = 1.15k\Omega$$

8-24

VARIABLE GAIN CMOS AMP

```

VDD 1 0 5V
M1 3 4 0 0 NMOS W=20U L=1U
M2 2 2 1 1 PMOS W=20U L=1U
R1 2 0 10K
M3 3 2 1 1 PMOS W=20U L=1U
M5 5 2 1 1 PMOS W=20U L=1U
M6 5 3 0 0 NMOS W=20U L=1U
M4 5 6 3 0 NMOS W=5U L=2U
VC 6 0 3V
VI 4 0 1.527V
.DC VI 1.47 1.6 0.005
.PLOT DC V(5)
.TF V(5) VI
.MODELSET V(2)=3.17V V(3)=1.53V V(5)=1.53V
.MODEL NMOS NMOS KP=60U VTO=0.8 GAMMA=0.5
.MODEL PMOS PMOS KP=30U VTO=-0.8 GAMMA=0.5
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

```

M3 3 2 1 1 PMOS W=20U L=1U
M5 5 2 1 1 PMOS W=20U L=1U
M6 5 3 0 0 NMOS W=20U L=1U
M4 5 6 3 0 NMOS W=5U L=2U
VC 6 0 4V
VI 4 0 1.527V
.DC VI 1.0 1.8 0.05
.PLOT DC V(5)
.TF V(5) VI
.MODELSET V(2)=3.17V V(3)=1.53V V(5)=1.53V
.MODEL NMOS NMOS KP=60U VTO=0.8 GAMMA=0.5
.MODEL PMOS PMOS KP=30U VTO=-0.8 GAMMA=0.5
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** DC TRANSFER CURVES THOM= 27.000 TEMP= 27.000

***** DC TRANSFER CURVES THOM= 27.000 TEMP= 27.000

VOLT (A)	V(5)	1.000E+00	2.000E+00	3.000E+00	4.000E+00	5.000E+00
1.470E+00	1.06E+00	+	+	+	+	+
1.475E+00	1.09E+00	+	+	+	+	+
1.480E+00	1.11E+00	+	+	+	+	+
1.485E+00	1.14E+00	+	+	+	+	+
1.490E+00	1.18E+00	+	+	+	+	+
1.495E+00	1.21E+00	+	+	+	+	+
1.500E+00	1.24E+00	+	+	+	+	+
1.505E+00	1.28E+00	+	+	+	+	+
1.510E+00	1.32E+00	+	+	+	+	+
1.515E+00	1.37E+00	+	+	+	+	+
1.520E+00	1.43E+00	+	+	+	+	+
1.525E+00	1.49E+00	+	+	+	+	+
1.530E+00	1.58E+00	+	+	+	+	+
1.535E+00	1.70E+00	+	+	+	+	+
1.540E+00	4.29E+00	+	+	+	+	+
1.545E+00	4.46E+00	+	+	+	+	+
1.550E+00	4.56E+00	+	+	+	+	+
1.555E+00	4.63E+00	+	+	+	+	+
1.560E+00	4.68E+00	+	+	+	+	+
1.565E+00	4.72E+00	+	+	+	+	+
1.570E+00	4.75E+00	+	+	+	+	+
1.575E+00	4.77E+00	+	+	+	+	+
1.580E+00	4.79E+00	+	+	+	+	+
1.585E+00	4.81E+00	+	+	+	+	+
1.590E+00	4.82E+00	+	+	+	+	+
1.595E+00	4.83E+00	+	+	+	+	+
1.600E+00	4.83E+00	+	+	+	+	+

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

```

+0:1 = 5.000E+00 0:2 = 3.171E+00 0:3 = 1.527E+00
+0:4 = 1.527E+00 0:5 = 1.525E+00 0:6 = 3.000E+00

```

**** MOSFETS

ELEMENT	0:M1	0:M2	0:M3	0:M5	0:M6	0:M4
MODEL	0:NMOS	0:PMOS	0:PMOS	0:PMOS	0:NMOS	0:NMOS
ID	3.171E-04	-3.172E-04	-3.172E-04	-3.172E-04	-5.961E-08	
IBS	0.	0.	0.	0.	-1.527E-14	
IRD	-1.527E-14	1.828E-14	3.473E-14	3.474E-14	-1.526E-14	-1.526E-14
VGS	1.527E+00	-1.828E+00	-1.828E+00	-1.828E+00	1.527E+00	1.472E+00
VDS	1.527E+00	-1.828E+00	-3.472E+00	-3.474E+00	1.525E+00	-1.198E-03
VBS	0.	0.	0.	0.	0.	-1.527E+00
VTH	8.000E-01	-8.000E-01	-8.000E-01	-8.000E-01	8.000E-01	1.141E+00
VDSAT	7.270E-01	-1.028E+00	-1.028E+00	-1.028E+00	7.271E-01	1.198E-03
BETA	1.200E-03	6.000E-04	6.000E-04	6.000E-04	1.200E-03	1.500E-04
GAM EFF	5.000E-01	5.000E-01	5.000E-01	5.000E-01	5.000E-01	5.000E-01
GM	8.724E-04	6.169E-04	6.169E-04	6.169E-04	8.726E-04	1.797E-07
GDS	0.	0.	0.	0.	0.	4.967E-05
GMB	2.816E-04	1.991E-04	1.991E-04	1.991E-04	2.816E-04	3.081E-08
CDTOT	0.	0.	0.	0.	0.	0.
CGTOT	0.	0.	0.	0.	0.	0.
CSTOT	0.	0.	0.	0.	0.	0.
CBTOT	0.	0.	0.	0.	0.	0.
CGS	0.	0.	0.	0.	0.	0.
CGD	0.	0.	0.	0.	0.	0.

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(5)/VI = 1.649E+01
INPUT RESISTANCE AT VI = 9.999E+19
OUTPUT RESISTANCE AT V(5) = 1.141E+03

```

VARIABLE GAIN CMOS AMP

```

VDD 1 0 5V
M1 3 4 0 0 NMOS W=20U L=1U
M2 2 2 1 1 PMOS W=20U L=1U
R1 2 0 10K

```

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

```

+0:1 = 5.000E+00 0:2 = 3.171E+00 0:3 = 1.527E+00
+0:4 = 1.527E+00 0:5 = 1.526E+00 0:6 = 4.000E+00

```

**** MOSFETS

ELEMENT	0:M1	0:M2	0:M3	0:M5	0:M6	0:M4
MODEL	0:NMOS	0:PMOS	0:PMOS	0:PMOS	0:NMOS	0:NMOS
ID	3.171E-04	-3.172E-04	-3.172E-04	-3.172E-04	3.172E-04	-5.961E-08
IBS	0.	0.	0.	0.	0.	-1.527E-14
IRD	-1.527E-14	1.828E-14	3.473E-14	3.473E-14	-1.527E-14	-1.527E-14
VGS	1.527E+00	-1.828E+00	-1.828E+00	-1.828E+00	1.527E+00	2.472E+00
VDS	1.527E+00	-1.828E+00	-3.472E+00	-3.473E+00	1.526E+00	-2.985E-04
VBS	0.	0.	0.	0.	0.	-1.527E+00
VTH	8.000E-01	-8.000E-01	-8.000E-01	-8.000E-01	8.000E-01	1.141E+00
VDSAT	7.270E-01	-1.028E+00	-1.028E+00	-1.028E+00	7.271E-01	2.985E-04
BETA	1.200E-03	6.000E-04	6.000E-04	6.000E-04	1.200E-03	1.500E-04
GAM EFF	5.000E-01	5.000E-01	5.000E-01	5.000E-01	5.000E-01	5.000E-01
GM	8.724E-04	6.169E-04	6.169E-04	6.169E-04	8.726E-04	4.478E-08
GDS	0.	0.	0.	0.	0.	1.996E-04
GMB	2.816E-04	1.991E-04	1.991E-04	1.991E-04	2.816E-04	7.677E-09
CDTOT	0.	0.	0.	0.	0.	0.
CGTOT	0.	0.	0.	0.	0.	0.
CSTOT	0.	0.	0.	0.	0.	0.
CBTOT	0.	0.	0.	0.	0.	0.
CGS	0.	0.	0.	0.	0.	0.
CGD	0.	0.	0.	0.	0.	0.

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(5)/VI = 3.369E+00
INPUT RESISTANCE AT VI = 9.999E+19
OUTPUT RESISTANCE AT V(5) = 1.145E+03

```

8-25

8.24

$$I_{D1} = I_{D2} = \frac{1}{2} I_{D6} = 100 \mu A = I_{D3}$$

$$I_{D8} = 200 \mu A$$

$$a = \frac{1}{2} g_{m1} (2r_{o2} \parallel r_{o3}) \frac{g_{m8} (21k)}{1 + g_{m8} (21k)}$$

$$= \frac{1}{2} (693 \mu) (222k) (0.954)$$

$$= 73.4$$

$$g_{m1} = \sqrt{2(100 \mu)(60 \mu) 40}$$

$$= 693 \mu A/V$$

$$r_{o2} = r_{o3} = \frac{1}{\lambda I_D} = \frac{1}{0.03 (100 \mu)}$$

$$= 333k$$

$$g_{m8} = \sqrt{2(200 \mu)(60 \mu) 40}$$

$$= 980 \mu A/V$$

$$f = \frac{1k}{1k + 20k} = \frac{1}{21}$$

$$T = af = 3.5$$

$$A = \frac{a}{1+T} = \frac{73.4}{4.5} = 16.3 = \frac{V_o}{V_i}$$

$$R_o = \frac{r_{out}}{1+T} = \frac{973}{4.5}$$

$$= 216 \Omega$$

$$r_{out} = 21k \parallel \frac{1}{g_{m8}}$$

$$= 21k \parallel 1.02k$$

$$= 973 \Omega$$

CHOS FEEDBACK AMP

```

VDD 1 0 5V
VSS 9 0 -5V
M4 2 2 1 1 PMOS W=20U L=1U
I1 2 3 100UA
M5 3 3 9 9 NMOS W=20U L=1U
M6 6 3 9 9 NMOS W=40U L=1U
M1 1 4 6 9 NMOS W=40U L=1U
M2 5 7 6 9 NMOS W=40U L=1U
M3 5 2 1 1 PMOS W=20U L=1U
M8 1 5 8 9 NMOS W=40U L=1U
M7 8 3 9 9 NMOS W=40U L=1U
RP 8 7 20K
RE 7 0 1K
VI 4 0 0V
.TF V(8) VI
.MODEL NMOS NMOS KP=60U VTO=0.8 LAMBDA=0.03
.MODEL PMOS PMOS KP=30U VTO=-0.8 LAMBDA=0.03
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.END

```

***** OPERATING POINT INFORMATION THIN= 27.000 TEMP= 27.000

+0:1	= 5.000E+00 0:2	= 3.634E+00 0:3	= -3.798E+00
+0:4	= 0. 0:5	= 1.413E+00 0:6	= -1.077E+00
+0:7	= 9.599E-03 0:8	= 2.016E-01 0:9	= -5.000E+00

**** MOSFETS

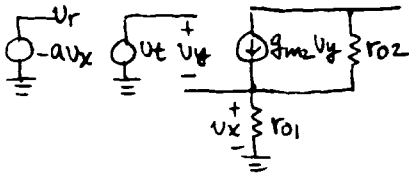
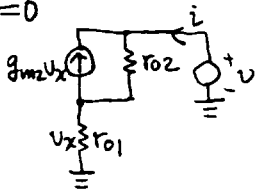
ELEMENT	0:M4	0:M5	0:M6	0:M1	0:M2	0:M3
MODEL	0:PMOS	0:NMOS	0:NMOS	0:NMOS	0:NMOS	0:PMOS
ID	-1.000E-04	1.000E-04	2.158E-04	1.094E-04	1.064E-04	-1.064E-04
IBS	0.	0.	0.	-3.922E-14	-3.922E-14	0.
IED	1.366E-14	-1.201E-14	-3.922E-14	-1.000E-13	-6.413E-14	3.587E-14
VGS	-1.365E+00	1.201E+00	1.201E+00	1.077E+00	1.087E+00	-1.365E+00
VDS	-1.365E+00	1.201E+00	3.922E+00	6.077E+00	2.491E+00	-3.586E+00
VBS	0.	0.	0.	-3.922E+00	-3.922E+00	0.
VTH	-8.000E-01	8.000E-01	8.000E-01	8.000E-01	8.000E-01	-8.000E-01
VDSAT	-5.659E-01	4.011E-01	4.011E-01	2.776E-01	2.872E-01	-5.659E-01
BETA	6.246E-04	1.243E-03	2.682E-03	2.838E-03	2.579E-03	6.646E-04
GAM KFF	0.	0.	0.	0.	0.	0.
GM	3.534E-04	4.986E-04	1.076E-03	7.878E-04	7.409E-04	3.761E-04
GDS	2.882E-06	2.896E-06	5.791E-06	2.775E-06	2.970E-06	2.882E-06
GMS	0.	0.	0.	0.	0.	0.
CUTOT	0.	0.	0.	0.	0.	0.
COTOT	0.	0.	0.	0.	0.	0.
CSTOT	0.	0.	0.	0.	0.	0.
CBTOT	0.	0.	0.	0.	0.	0.
CGS	0.	0.	0.	0.	0.	0.
CGD	0.	0.	0.	0.	0.	0.

ELEMENT	0:M8	0:M7
MODEL	0:NMOS	0:NMOS
ID	2.328E-04	2.232E-04
IBS	-5.202E-14	0.
IED	-1.000E-13	-5.202E-14
VGS	1.211E+00	1.201E+00
VDS	4.798E+00	5.201E+00
VBS	-5.201E+00	0.
VTH	8.000E-01	8.000E-01
VDSAT	4.118E-01	4.011E-01
BETA	2.745E-03	2.775E-03
GAM KFF	0.	0.
GM	1.131E-03	1.113E-03
GDS	6.104E-06	5.791E-06
GMS	0.	0.
CUTOT	0.	0.
COTOT	0.	0.
CSTOT	0.	0.
CBTOT	0.	0.
CGS	0.	0.
CGD	0.	0.

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(8)/VI	= 1.662E+01
INPUT RESISTANCE AT VI	= 9.999E+19
OUTPUT RESISTANCE AT V(8)	= 1.707E+02

8.25

Consider a as the controlled source. $a=0$ 

$$\frac{v_x}{r_01} = g_{m2} v_x + \frac{v_x - v}{r_02}$$

$$R_{out}(a=0) = \frac{v}{i} = \frac{v}{v_x/r_01}$$

$$\approx g_{m2} r_01 r_02$$

The output is shorted

$$v_x = g_{m2}(v_t - v_x)(r_01 || r_02)$$

$$v_x = \frac{g_{m2}(r_01 || r_02)}{1 + g_{m2}(r_01 || r_02)} v_t$$

$$R(\text{short}) = a \frac{g_{m2}(r_01 || r_02)}{1 + g_{m2}(r_01 || r_02)}$$

 $R(\text{open}) = 0$ ($v_x = 0$ when the output is open.)

$$R_{out} = R_{out}(a=0) \frac{1 + R(\text{short})}{1 + R(\text{open})}$$

$$\approx g_{m2} r_01 r_02 \frac{1 + a \frac{g_{m2}(r_01 || r_02)}{1 + g_{m2}(r_01 || r_02)}}{1 + 0}$$

$$\approx a g_{m2} r_01 r_02$$

$$g_{m1} = g_{m2} = \frac{2I_D}{V_{ov}} = \frac{2 \times 100 \mu A}{0.3 V} = 0.67 \text{ mA/V}$$

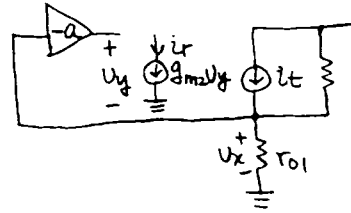
$$r_01 = r_02 = \frac{1}{\lambda_n I_D} = \frac{1}{0.03 V^{-1} \times 100 \mu A} = 330 \text{ k}\Omega$$

$$R_{out} \approx a g_{m2} r_01 r_02$$

$$= 10^3 \times 0.67 \text{ m} \times (330 \text{ k})^2 = 73 \text{ G}\Omega$$

$$\frac{v_o}{v_i} \approx -g_{m1} R_{out} = -0.67 \text{ m} \times 73 \text{ G} = -4.9 \times 10^7$$

8.26

(a) g_{m2} is the controlled source.

$$R_{out}(g_{m2}=0) = r_01 + r_02$$

$$R(\text{short}) = (r_01 || r_02)(a+1)g_{m2}$$

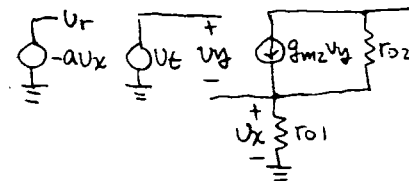
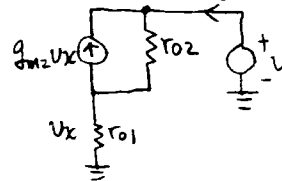
$$R(\text{open}) = 0$$

$$R_{out} = R_{out}(g_{m2}=0) \frac{1 + R(\text{short})}{1 + R(\text{open})}$$

$$= (r_01 + r_02) \frac{1 + (r_01 || r_02)(a+1)g_{m2}}{1 + 0}$$

$$= r_01 + r_02 + (a+1)g_{m2} r_01 r_02$$

$$\approx a g_{m2} r_01 r_02$$

(b) a is the controlled source. $a=0$ 

$$\frac{v_x}{r_01} = g_{m2} v_x + \frac{v_x - v}{r_02}$$

$$R_{out}(a=0) = \frac{v}{i} = \frac{v}{v_x/r_01}$$

$$= g_{m2} r_01 r_02 + r_01 - r_02$$

$$\approx g_{m2} r_01 r_02$$

The output is short

$$v_x = g_{m2}(v_t - v_x)(r_01 || r_02)$$

$$v_x = \frac{g_{m2}(r_01 || r_02)}{1 + g_{m2}(r_01 || r_02)} v_t$$

8-27

$$R(\text{short}) = a \frac{g_{m2}(r_{o1} \parallel r_{o2})}{1 + g_{m2}(r_{o1} \parallel r_{o2})}$$

$R(\text{open}) = 0$ ($v_x = 0$ when the output is open.)

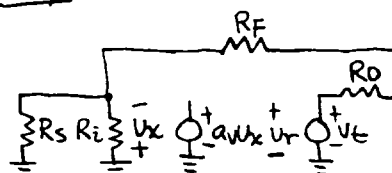
$$R_{out} = R_{out}(a=0) \frac{1 + R(\text{short})}{1 + R(\text{open})}$$

$$\approx g_{m2} r_{o1} r_{o2} \frac{1 + a \frac{g_{m2}(r_{o1} \parallel r_{o2})}{1 + g_{m2}(r_{o1} \parallel r_{o2})}}{1 + 0}$$

$$\approx a g_{m2} r_{o1} r_{o2}$$

(c) The results are the same, as they should be, even though the terms $R_{out}(k=0)$, $R(\text{open})$, and $R(\text{short})$ differ in (a) and (b).

8.27



$$R = \frac{R_S \parallel R_i}{R_o + R_F + R_S \parallel R_i} a_v$$

$$= \frac{10k \parallel 1M}{10k + 100k + 10k \parallel 1M} 200 = 16.5$$

$$A_{vo} = -\frac{R_F}{R_S} = -\frac{100k}{10k} = -10$$

$$d = \frac{v_o}{v_i} \big|_{a_v=0} = \frac{R_i \parallel (R_F + R_o)}{R_S + R_i \parallel (R_F + R_o)} \frac{R_o}{R_F + R_o}$$

$$= \frac{1M \parallel (100k + 10k)}{10k + 1M \parallel (100k + 10k)} \frac{10k}{100k + 10k} = 0.082$$

$$A = A_{vo} \frac{R}{1 + R} + \frac{d}{1 + R} = -10 \frac{16.5}{1 + 16.5} + \frac{0.082}{1 + 16.5}$$

$$= -9.4$$

$$R_{in}(a_v=0) = R_S + R_i \parallel (R_F + R_o)$$

$$= 10k + 1M \parallel (100k + 10k) = 1.1 \times 10^5 \Omega$$

$$R(\text{short input}) = R = 16.5$$

$$R(\text{open input}) = \frac{R_i}{R_o + R_F + R_i} a_v$$

$$= \frac{1M}{10k + 100k + 1M} 200 = 180$$

$$R_{in} = R_{in}(a_v=0) \frac{1 + R(\text{short})}{1 + R(\text{open})} = 1.1 \times 10^5 \frac{1 + 16.5}{1 + 180}$$

$$= 1.1 \times 10^4 \Omega = 11k\Omega$$

$$R_{out}(a_v=0) = R_o \parallel [R_F + R_S \parallel R_i]$$

$$= 10k \parallel [100k + 10k \parallel 1M] = 9.2k\Omega$$

$$R(\text{short output}) = 0$$

$$R(\text{open output}) = R = 16.5$$

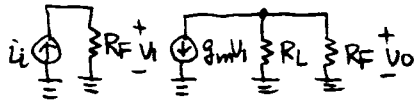
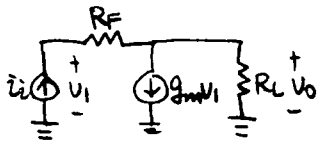
$$R_{out} = R_{out}(a_v=0) \frac{1 + R(\text{short})}{1 + R(\text{open})}$$

$$= 9.2k \frac{1 + 0}{1 + 16.5} = 0.52k\Omega = 520\Omega$$

8-28

8.28

(a)



$$g_m = \sqrt{2k' \frac{W}{L} I_D} = \sqrt{2 \times 180 \times 10^{-6} \times 100 \times 0.5 \times 10^{-3}}$$

$$= 4.2 \times 10^{-3} \text{ A/V}$$

$$a = R_F (-g_m) (R_L \parallel R_F) = -100k \times 4.2m (100k \parallel 15k)$$

$$= -5.5 \times 10^6 \Omega$$

$$f = -\frac{1}{R_F} = -\frac{1}{100k\Omega}$$

shunt-shunt feedback

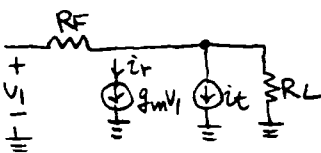
$$a_f = 55$$

$$A = \frac{a}{1+a_f} = \frac{-5.5 \times 10^6}{1+55} = -9.8 \times 10^4 \Omega = -98k\Omega$$

$$R_i = \frac{R_F}{1+a_f} = \frac{100k}{1+55} = 1.8k\Omega$$

$$R_o = \frac{R_L \parallel R_F}{1+a_f} = \frac{15k \parallel 100k}{1+55} = 230\Omega$$

(b)



$$R = g_m R_L = 4.2m \times 15k = 63$$

$$A_{\infty} = -R_F = -100k\Omega$$

$$d = \frac{V_o}{i_i} \bigg|_{g_m=0} = R_L = 15k\Omega$$

$$A = A_{\infty} \frac{R}{1+R} + \frac{d}{1+R} = -100k \frac{63}{1+63} + \frac{15k}{1+63}$$

$$= -98k\Omega$$

$$R_{in}(g_m=0) = R_F + R_L = 100k + 15k = 115k$$

$$R(\text{short input}) = 0$$

$$R(\text{open input}) = R = 63$$

$$R_{in} = R_{in}(g_m=0) \frac{1+R(\text{short})}{1+R(\text{open})}$$

$$= 115k \frac{1+0}{1+63} = 1.8k\Omega$$

$$R_{out}(g_m=0) = R_L = 15k\Omega$$

$$R(\text{short}) = 0$$

$$R(\text{open}) = R = 63$$

$$R_{out} = R_{out}(g_m=0) \frac{1+R(\text{short})}{1+R(\text{open})}$$

$$= 15k \frac{1+0}{1+63} = 230\Omega$$

8.29

(a)



$$g_m = \frac{I_C}{V_T} = \frac{1 \text{ mA}}{26 \text{ mV}} = 38 \text{ mA/V}$$

$$r_{\pi} = \frac{\beta_0}{g_m} = \frac{20}{0.038} = 5.2 \text{ k}\Omega$$

$$r_o = \frac{V_A}{I_C} = \frac{100}{0.5} = 100 \text{ k}\Omega$$

$$a = (r_{\pi} \parallel R_F)(-g_m)(r_o \parallel R_L \parallel R_F)$$

$$= -(5.2 \text{ k} \parallel 2 \text{ k}) 0.038 (100 \text{ k} \parallel 2 \text{ k} \parallel 2 \text{ k})$$

$$= -5.4 \times 10^4 \Omega$$

$$f = -\frac{1}{R_F} = -\frac{1}{2 \text{ k}\Omega}$$

$$af = 27$$

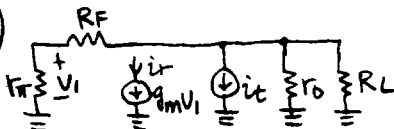
shunt-shunt feedback

$$A = \frac{a}{1+af} = \frac{-5.4 \times 10^4}{1+27} = -1.9 \text{ k}\Omega$$

$$R_i = \frac{r_{\pi} \parallel R_F}{1+af} = \frac{5.2 \text{ k} \parallel 2 \text{ k}}{1+27} = 52 \Omega$$

$$R_o = \frac{r_o \parallel R_L \parallel R_F}{1+af} = \frac{100 \text{ k} \parallel 2 \text{ k} \parallel 2 \text{ k}}{1+27} = 35 \Omega$$

(b)



$$R = \frac{r_{\pi}}{R_F + r_{\pi}} g_m$$

$$= \frac{[100 \text{ k} \parallel 2 \text{ k} \parallel (2 \text{ k} + 5.2 \text{ k})] \cdot 5.2 \text{ k}}{2 \text{ k} + 5.2 \text{ k}} \cdot 3.8 \times 10^{-2}$$

$$= 42$$

$$A_{\infty} = -R_F = -2 \text{ k}\Omega$$

$$d = \frac{v_o}{v_i} \bigg|_{g_m=0} = \left\{ r_{\pi} \parallel [R_F + (r_o \parallel R_L)] \right\} \frac{r_o \parallel R_L}{R_F + (r_o \parallel R_L)}$$

$$= \left\{ 5.2 \text{ k} \parallel [2 \text{ k} + (100 \text{ k} \parallel 2 \text{ k})] \right\} \frac{100 \text{ k} \parallel 2 \text{ k}}{2 \text{ k} + (100 \text{ k} \parallel 2 \text{ k})}$$

$$= 1.1 \text{ k}\Omega$$

$$A = A_{\infty} \frac{R}{1+R} + \frac{d}{1+R} = -2 \text{ k} \frac{42}{1+42} + \frac{1.1 \text{ k}}{1+42}$$

$$= -1.9 \text{ k}\Omega$$

$$R_{in}(g_m=0) = r_{\pi} \parallel [R_F + (r_o \parallel R_L)]$$

$$= 5.2 \text{ k} \parallel [2 \text{ k} + (100 \text{ k} \parallel 2 \text{ k})] = 2.2 \text{ k}$$

$$R(\text{short input}) = 0$$

$$R(\text{open input}) = R = 42$$

$$R_{in} = R_{in}(g_m=0) \frac{1+R(\text{short})}{1+R(\text{open})}$$

$$= 2.2 \text{ k} \frac{1+0}{1+42} = 51 \Omega$$

$$R_{out}(g_m=0) = r_o \parallel R_L \parallel (R_F + r_{\pi})$$

$$= 100 \text{ k} \parallel 2 \text{ k} \parallel (2 \text{ k} + 5.2 \text{ k}) = 1.5 \text{ k}\Omega$$

$$R(\text{short output}) = 0$$

$$R(\text{open output}) = R = 42$$

$$R_{out} = R_{out}(g_m=0) \frac{1+R(\text{short})}{1+R(\text{open})}$$

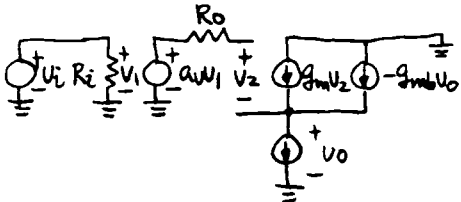
$$= 1.5 \text{ k} \frac{1+0}{1+42} = 35 \Omega$$

8-30

8.30

(a)

The basic amplifier without the feedback signal inserted at the inverting input of the opamp



$$g_m = \sqrt{2k \frac{W}{L} I_D} = \sqrt{2 \times 180 \times 10^{-6} \times 100 \times 0.5 \times 10^{-3}} \\ = 4.2 \times 10^{-3} \text{ A/V}$$

$$g_{mb} = \frac{\gamma}{2\sqrt{2\phi_f + V_{SB}}} g_m = \frac{\gamma}{2\sqrt{2\phi_f}} g_m \\ = \frac{0.3}{2\sqrt{2 \times 0.3}} 4.2 \times 10^{-3} = 8.1 \times 10^{-4} \text{ A/V}$$

$$V_o = g_m (a_v V_i - V_o) \frac{1}{g_{mb}}$$

$$a = \frac{V_o}{V_i} = a_v \frac{g_m}{g_m + g_{mb}}$$

$$f = 1$$

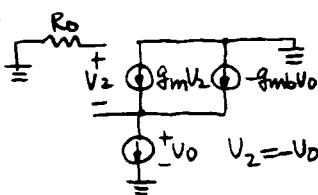
$$a_f = a_v \frac{g_m}{g_m + g_{mb}} = 1000 \frac{4.2}{4.2 + 0.81} = 838$$

$$A = \frac{a}{1 + a_f} = \frac{838}{1 + 838} = 0.999$$

$$r_{ia} = R_i$$

$$R_{in} = r_{ia}(1 + a_f) = R_i(1 + a_f) \\ = 1\text{M}(1 + 838) = 839\text{M}\Omega$$

$$V_i = 0$$

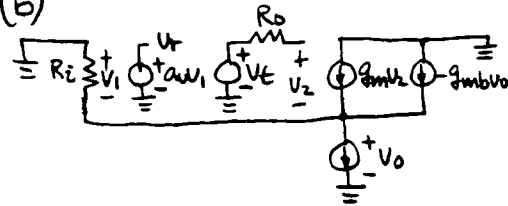


$$r_{oa} = \frac{1}{g_m} \parallel \frac{1}{g_{mb}} = \frac{1}{g_m + g_{mb}}$$

$$R_{out} = \frac{r_{oa}}{1 + a_f} = \frac{1}{g_m + g_{mb}} \frac{1}{1 + a_f}$$

$$= \frac{1}{4.2 \times 10^{-3} + 8.1 \times 10^{-4}} \frac{1}{1 + 838} \\ = 0.238 \Omega$$

(b)



$$V_o = g_m (V_i - V_o) \left(\frac{1}{g_{mb}} \parallel R_i \right)$$

$$V_o = \frac{g_m}{\frac{1}{R_i} + g_m + g_{mb}}$$

$$R = a_v \frac{g_m}{\frac{1}{R_i} + g_m + g_{mb}}$$

$$\approx a_v \frac{g_m}{g_m + g_{mb}}$$

$$= 838$$

$$A_{vo} = \frac{V_o}{V_i} \bigg|_{a_v=1} = 1 \quad (V_i = 0 \text{ and } V_o = V_i)$$

$$d = \frac{V_o}{V_i} \bigg|_{a_v=0} = \frac{\frac{1}{g_m} \parallel \frac{1}{g_{mb}}}{R_i + \frac{1}{g_m} \parallel \frac{1}{g_{mb}}}$$

$$= \frac{1}{\frac{1}{g_m + g_{mb}} + R_i}$$

$$\approx \frac{1}{(g_m + g_{mb}) R_i}$$

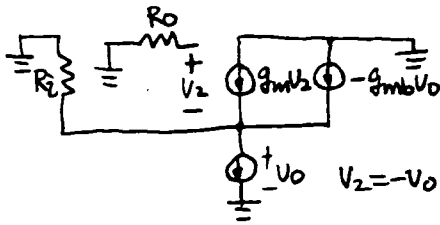
$$= \frac{1}{(4.2 \times 10^{-3} + 8.1 \times 10^{-4}) 10^6}$$

$$= 2.00 \times 10^{-4}$$

$$A = A_{vo} \frac{R}{1 + R} + \frac{d}{1 + R} \\ = 1 \frac{838}{1 + 838} + \frac{2.00 \times 10^{-4}}{1 + 838} \\ = 0.999$$

8.30 continued

$$a_v = 0$$



$$R_{in}(a_v=0) = R_i + \frac{1}{g_m} \parallel \frac{1}{g_{mb}} \approx R_i = 1 \text{ M}\Omega$$

$$R(\text{short}) = R = 838$$

$$R(\text{open}) = 0 \quad (v_i = 0)$$

$$R_{in} = R_{in}(a_v=0) \frac{1+R(\text{short})}{1+R(\text{open})} \approx R_i \frac{1+R}{1+0} \\ = R_i(1+R) = 1 \text{ M}(1+838) = 839 \text{ M}\Omega$$

$$R_{out}(a_v=0) = R_i \parallel \frac{1}{g_m} \parallel \frac{1}{g_{mb}} \approx \frac{1}{g_m} \parallel \frac{1}{g_{mb}} \\ = \frac{1}{g_m + g_{mb}} = \frac{1}{4.2 \times 10^{-3} + 8.1 \times 10^{-4}} = 200 \Omega$$

$$R(\text{short}) = 0 \quad (v_o = 0)$$

$$R(\text{open}) = R$$

$$R_{out} = R_{out}(a_v=0) \frac{1+R(\text{short})}{1+R(\text{open})} \\ \approx \frac{1}{g_m + g_{mb}} \frac{1+0}{1+R} = \frac{1}{g_m + g_{mb}} \frac{1}{1+R} \\ = 200 \frac{1}{1+838} = 0.238 \Omega$$

8.31

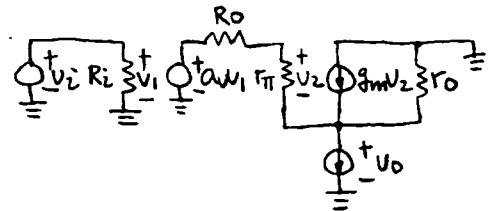
$$g_m = \frac{I_c}{V_T} = \frac{0.5 \text{ mA}}{26 \text{ mV}} = 19 \text{ mA/V}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{19 \text{ m}} = 5.2 \text{ k}\Omega$$

$$r_o = \frac{V_A}{I_c} = \frac{50}{0.5 \text{ m}} = 100 \text{ k}\Omega$$

(a).

The basic amplifier without the feedback signal inserted at the inverting input of the op amp



$$v_o = g_m [(a_v v_i - v_o) \frac{r_\pi}{R_o + r_\pi}] [r_o \parallel (R_o + r_\pi)]$$

$$a = \frac{v_o}{v_i} = a_v \frac{g_m \frac{r_\pi}{R_o + r_\pi} [r_o \parallel (R_o + r_\pi)]}{1 + g_m \frac{r_\pi}{R_o + r_\pi} [r_o \parallel (R_o + r_\pi)]} \\ = 1000 \frac{19 \text{ m} \frac{5.2 \text{ k}}{10 \text{ k} + 5.2 \text{ k}} [100 \text{ k} \parallel (10 \text{ k} + 5.2 \text{ k})]}{1 + 19 \text{ m} \frac{5.2 \text{ k}}{10 \text{ k} + 5.2 \text{ k}} [100 \text{ k} \parallel (10 \text{ k} + 5.2 \text{ k})]} \\ = 988$$

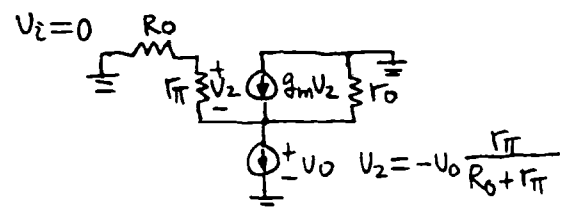
$$f = 1$$

$$a_f = 988$$

$$A = \frac{a}{1+a_f} = \frac{988}{1+988} = 0.999$$

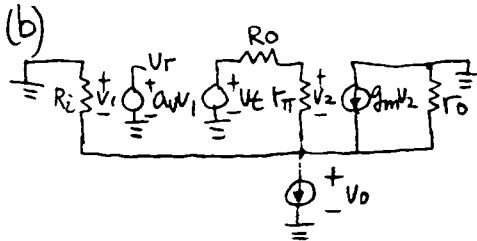
$$r_{ia} = R_i$$

$$R_{in} = r_{ia}(1+a_f) = R_i(1+a_f) \\ = 1 \text{ M}(1+988) = 989 \text{ M}\Omega$$



$g_m v_2 = -g_m \frac{r_\pi}{R_o + r_\pi} v_o$ is equivalent to a resistance of

$$\begin{aligned} \frac{1}{g_m} \frac{R_o + r_\pi}{r_\pi} &= \frac{1}{\beta} (R_o + r_\pi) \\ r_{oa} &= (R_o + r_\pi) \parallel \frac{1}{\beta} (R_o + r_\pi) \parallel r_o \\ &\approx (R_o + r_\pi) \left(1 \parallel \frac{1}{\beta}\right) \\ &= \frac{1}{\beta + 1} (R_o + r_\pi) \\ R_{out} &= \frac{r_{oa}}{1 + a_f} \approx \frac{R_o + r_\pi}{\beta + 1} \frac{1}{1 + a_f} \\ &= \frac{10k + 5.2k}{100 + 1} \frac{1}{1 + 988} = 0.152 \Omega \end{aligned}$$



$$v_o = g_m \left[(v_e - v_o) \frac{r_\pi}{R_o + r_\pi} \right] [r_o \parallel (R_o + r_\pi) \parallel R_i]$$

$$v_o = \frac{g_m \frac{r_\pi}{R_o + r_\pi} [r_o \parallel (R_o + r_\pi) \parallel R_i]}{1 + g_m \frac{r_\pi}{R_o + r_\pi} [r_o \parallel (R_o + r_\pi) \parallel R_i]}$$

$$R = a_v \frac{g_m \frac{r_\pi}{R_o + r_\pi} [r_o \parallel (R_o + r_\pi) \parallel R_i]}{1 + g_m \frac{r_\pi}{R_o + r_\pi} [r_o \parallel (R_o + r_\pi) \parallel R_i]}$$

$$= 1000 \frac{19m \frac{5.2k}{10k + 5.2k} [100k \parallel (10k + 5.2k) \parallel 1M]}{1 + 19m \frac{5.2k}{10k + 5.2k} [100k \parallel (10k + 5.2k) \parallel 1M]}$$

$$= 988$$

$$A_\infty = \frac{v_o}{v_i} \Big|_{a_v \rightarrow \infty} = 1 \quad (v_i = 0 \text{ and } v_o = v_2)$$

$$d = \frac{v_o}{v_2} \Big|_{a_v = 0} = \frac{(R_o + r_\pi) \parallel \frac{1}{g_m} \frac{R_o + r_\pi}{r_\pi} \parallel r_o}{R_i + (R_o + r_\pi) \parallel \frac{1}{g_m} \frac{R_o + r_\pi}{r_\pi} \parallel r_o}$$

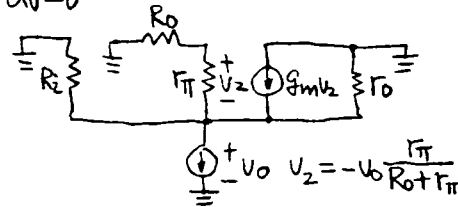
$$\approx \frac{(R_o + r_\pi) \parallel \frac{1}{\beta} (R_o + r_\pi)}{R_i} = \frac{R_o + r_\pi}{(\beta + 1) R_i}$$

$$= \frac{10k + 5.2k}{(100 + 1) 1M} = 1.50 \times 10^{-4}$$

8.31 continued

$$\begin{aligned} A &= A_\infty \frac{R}{1 + R} + \frac{d}{1 + R} = 1 \frac{988}{1 + 988} + \frac{1.50 \times 10^{-4}}{1 + 988} \\ &= 0.999 \end{aligned}$$

$a_v = 0$



$$\begin{aligned} R_{in}(a_v = 0) &= R_i + [(R_o + r_\pi) \parallel \frac{1}{g_m} \frac{R_o + r_\pi}{r_\pi} \parallel r_o] \\ &\approx R_i + (R_o + r_\pi) \left(1 \parallel \frac{1}{\beta}\right) = R_i + \frac{R_o + r_\pi}{\beta + 1} \end{aligned}$$

$$\approx R_i$$

$$R(\text{short}) = R = 988$$

$$R(\text{open}) = 0 \quad (v_i = 0)$$

$$\begin{aligned} R_{in} &= R_{in}(a_v = 0) \frac{1 + R(\text{short})}{1 + R(\text{open})} \approx R_i (1 + R) \\ &= 1M (1 + 988) = 989M \Omega \end{aligned}$$

$$R_{out}(a_v = 0) = (R_o + r_\pi) \parallel \frac{1}{g_m} \frac{R_o + r_\pi}{r_\pi} \parallel r_o \parallel R_i$$

$$\approx (R_o + r_\pi) \left(1 \parallel \frac{1}{\beta}\right) = \frac{R_o + r_\pi}{\beta + 1}$$

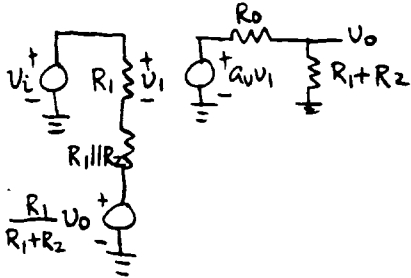
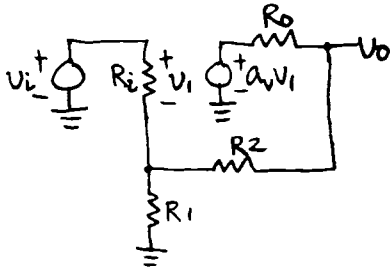
$$R(\text{short}) = 0 \quad (v_o = 0)$$

$$R(\text{open}) = R = 988$$

$$R_{out} = R_{out}(a_v = 0) \frac{1 + R(\text{short})}{1 + R(\text{open})}$$

$$\approx \frac{R_o + r_\pi}{\beta + 1} \frac{1}{1 + R} = \frac{10k + 5.2k}{100 + 1} \frac{1}{1 + 988}$$

$$= 0.152 \Omega$$

8.32
(a)

$$a = \frac{R_2}{R_2 + (R_1 \parallel R_0)} a_v \frac{R_1 + R_2}{R_0 + R_1 + R_2}$$

$$= \frac{1\text{M}}{1\text{M} + (1\text{k} \parallel 5\text{k})} 10^4 \frac{1\text{k} + 5\text{k}}{100 + 1\text{k} + 5\text{k}} = 9.83 \times 10^3$$

$$f = \frac{R_1}{R_1 + R_2} = \frac{1\text{k}}{1\text{k} + 5\text{k}} = 0.167$$

$$af = 1.64 \times 10^3$$

$$A = \frac{a}{1 + af} = \frac{9.83 \times 10^3}{1 + 1.64 \times 10^3} = 6$$

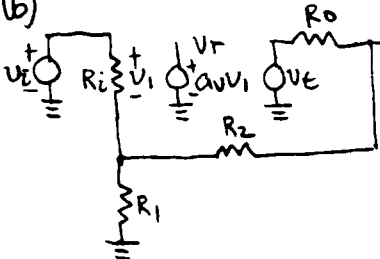
$$Z_{ia} = R_i + (R_1 \parallel R_2) = 1\text{M} + (1\text{k} \parallel 5\text{k}) = 1\text{M}\Omega$$

$$Z_i = Z_{ia}(1 + af) = 1\text{M}(1 + 1.64 \times 10^3) = 1.64\text{G}\Omega$$

$$Z_{oa} = R_0 \parallel (R_1 + R_2) = 100 \parallel (1\text{k} + 5\text{k}) = 98.4\Omega$$

$$Z_o = \frac{Z_{oa}}{1 + af} = \frac{98.4}{1 + 1.64 \times 10^3} = 0.06\Omega$$

(b)



$$R = \frac{R_2 \parallel R_1}{R_0 + R_2 + (R_2 \parallel R_1)} a_v$$

$$= \frac{1\text{M} \parallel 1\text{k}}{100 + 5\text{k} + (1\text{M} \parallel 1\text{k})} 10^4 = 1.64 \times 10^3$$

$$A_{\infty} = \frac{R_1 + R_2}{R_1} = \frac{1\text{k} + 5\text{k}}{1\text{k}} = 6$$

$$d = \frac{v_o}{v_i} \bigg|_{a_v=0} = \frac{R_1 \parallel (R_2 + R_0)}{R_i + [R_1 \parallel (R_2 + R_0)]} \frac{R_0}{R_2 + R_0}$$

$$= \frac{1\text{k} \parallel (5\text{k} + 100)}{1\text{M} + [1\text{k} \parallel (5\text{k} + 100)]} \frac{100}{5\text{k} + 100} = 1.64 \times 10^{-5}$$

$$A = A_{\infty} \frac{R}{1 + R} + \frac{d}{1 + R} = 6$$

$$R_{in}(a_v=0) = R_i + [R_1 \parallel (R_2 + R_0)]$$

$$= 1\text{M} + [1\text{k} \parallel (5\text{k} + 100)] = 1\text{M}\Omega$$

$$R(\text{short}) = R = 1.64 \times 10^3$$

$$R(\text{open}) = 0$$

$$R_{in} = R_{in}(a_v=0) \frac{1 + R(\text{short})}{1 + R(\text{open})}$$

$$= 1\text{M} \frac{1 + 1.64 \times 10^3}{1 + 0} = 1.64\text{G}\Omega$$

$$R_{out}(a_v=0) = R_0 \parallel [R_2 + (R_1 \parallel R_i)]$$

$$= 100 \parallel [5\text{k} + (1\text{M} \parallel 1\text{k})] = 98.4\Omega$$

$$R(\text{short}) = 0$$

$$R(\text{open}) = R = 1.64 \times 10^3$$

$$R_{out} = R_{out}(a_v=0) \frac{1 + R(\text{short})}{1 + R(\text{open})}$$

$$= 98.4 \frac{1 + 0}{1 + 1.64 \times 10^3} = 0.06\Omega$$

8-34

(C)

```

RETURN RATIO
.SUBCKT AMP (1 2)
RAMP 4 0 0 1 1K4
R1 1 0 1MEG
R0 3 4 100
R1 1 0 1K
R2 2 3 5K
.ENDS AMP

.OPTIONS NOMOD
XKRV (11 12) AMP
VF 12 11 AC 1

XKRI (21 22) AMP
IF 0 31 AC 1
VDUMMY1 31 21 0
VDUMMY2 22 31 0

.AC DEC 1 1K 1G
.PRINT AC KRV=PAR('VM(12)/VM(11)*COS(3.14*(VF(12)-VF(11))/180)')\
RV=PAR('VM(12)/VM(11)*SIN(3.14*(VF(12)-VF(11))/180)')\
KR=PAR('IM(VDUMMY2)/IM(VDUMMY1)*COS(3.14*(IP(VDUMMY2)-IP(VDUMMY1))/180)')\
KR=PAR('IM(VDUMMY2)/IM(VDUMMY1)*SIN(3.14*(IP(VDUMMY2)-IP(VDUMMY1))/180)')\
.WIDTH OUT=80
.OPTIONS SPICE
.END

```

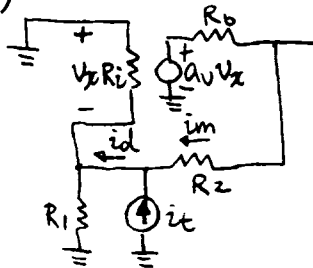
***** AC ANALYSIS

TNO= 27.000 TEMP= 27.000

FREQ	KRV	RV	KR	KRI
9.9999E+02	1.000E+04	1.593E+01	1.959E+03	-3.119E+00
9.9999E+03	1.000E+04	1.593E+01	1.959E+03	-3.119E+00
1.0000E+05	1.000E+04	1.593E+01	1.959E+03	-3.119E+00
1.0000E+06	1.000E+04	1.593E+01	1.959E+03	-3.119E+00
1.0000E+07	1.000E+04	1.593E+01	1.959E+03	-3.119E+00
1.0000E+08	1.000E+04	1.593E+01	1.959E+03	-3.119E+00
1.0000E+09	1.000E+04	1.593E+01	1.959E+03	-3.119E+00

8.33

(a)



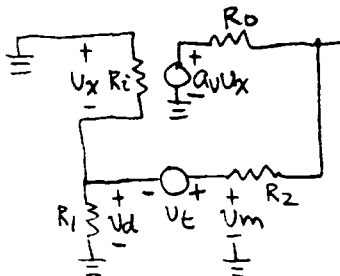
$$U = -i_d(R_i \parallel R_1)$$

$$i_m = \frac{a_v u_x (-u_x)}{R_0 + R_2} = \frac{(a_v + 1) u_x}{R_0 + R_2}$$

$$= -\frac{(a_v + 1)(R_i \parallel R_1)}{R_0 + R_2} i_d$$

$$R'_i = -\frac{i_m}{i_d} = \frac{(a_v + 1)(R_i \parallel R_1)}{R_0 + R_2}$$

$$= \frac{(10^4 + 1)(1M \parallel 1k)}{100 + 5k} = 1960$$



$$\frac{u_d}{R_i \parallel R_1} = \frac{-a_v u_d - u_m}{R_0 + R_2}$$

$$u_d \left(\frac{1}{R_i \parallel R_1} + \frac{a_v}{R_0 + R_2} \right) = -\frac{1}{R_0 + R_2} u_m$$

$$R'_v = -\frac{u_m}{u_d} = \frac{\frac{1}{R_i \parallel R_1} + \frac{a_v}{R_0 + R_2}}{\frac{1}{R_0 + R_2}}$$

$$= \frac{\frac{1}{1M \parallel 1k} + \frac{10^4}{100 + 5k}}{\frac{1}{100 + 5k}} = 10^4$$

$$\frac{1}{1+R} = \frac{1}{1+R'_v} + \frac{1}{1+R'_i}; R = 1640$$

(b)

$$R = \frac{R_i \parallel R_1}{R_0 + R_2 + (R_i \parallel R_1)} a_v$$

$$= \frac{1M \parallel 1k}{100 + 5k + (1M \parallel 1k)} 10^4 = 1.6 \times 10^3$$

$$\frac{1}{1+R} = \frac{1}{1+R'_v} + \frac{1}{1+R'_i}$$

$$= \frac{1}{1+10^4+j15.9} + \frac{1}{1+1959-j3.1}$$

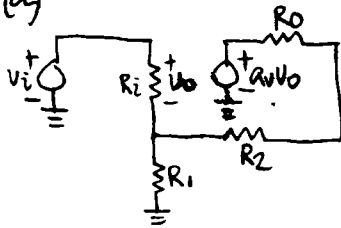
$$= 9.999 \times 10^{-5} - j1.59 \times 10^{-7} + 5.102 \times 10^{-4} + j8.07 \times 10^{-7}$$

$$= 6.102 \times 10^{-4} + j6.48 \times 10^{-7}$$

$$R \approx 1638$$

8.34

(a)



$$Z_i = h_{i1a} + h_{i1f} = 50 \text{ k}\Omega + 67 \text{ k}\Omega = 117 \text{ k}\Omega$$

$$h_{i1a} = \frac{v_{i1a}}{i_{i1a}} \bigg|_{v_{o2a}=0} = R_i = 50 \text{ k}\Omega$$

$$h_{i1f} = \frac{v_{i1f}}{i_{i1f}} \bigg|_{v_{o2f}=0} = R_1 \parallel R_2 = 67 \text{ k}\Omega$$

$$y_o = h_{22a} + h_{22f} = 10^{-6} \text{ S} + 3.3 \times 10^{-6} \text{ S} = 4.3 \times 10^{-6} \text{ S}$$

$$h_{22a} = \frac{i_{2a}}{v_{2a}} \bigg|_{i_{1a}=0} = \frac{1}{R_o} = \frac{1}{1 \text{ M}\Omega} = 10^{-6} \text{ S}$$

$$h_{22f} = \frac{i_{2f}}{v_{2f}} \bigg|_{i_{1f}=0} = \frac{1}{R_1 + R_2} = \frac{1}{300 \text{ k}\Omega} = 3.3 \times 10^{-6} \text{ S}$$

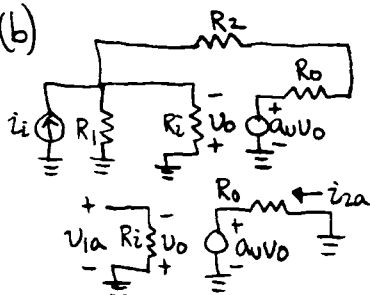
$$h_{21a} = \frac{i_{2a}}{i_{1a}} \bigg|_{v_{2a}=0} = -a_v \frac{R_i}{R_o} = -10^3 \frac{50 \text{ k}}{1 \text{ M}} = -50$$

$$f = h_{12f} = \frac{v_{1f}}{v_{2f}} \bigg|_{i_{1f}=0} = \frac{R_1}{R_1 + R_2} = \frac{2}{3}$$

$$a = -\frac{h_{21a}}{Z_i y_o} = -\frac{-50}{117 \text{ k} \times 4.3 \times 10^{-6}} = 99$$

$$a_f = 66$$

(b)



$$y_i = y_{i1a} + y_{i1f} = 2 \times 10^{-5} \text{ S} + 1.5 \times 10^{-5} \text{ S} = 3.5 \times 10^{-5} \text{ S}$$

$$y_{i1a} = \frac{i_{1a}}{v_{1a}} \bigg|_{v_{2a}=0} = \frac{1}{R_i} = \frac{1}{50 \text{ k}} = 2 \times 10^{-5} \text{ S}$$

$$y_{i1f} = \frac{i_{1f}}{v_{1f}} \bigg|_{v_{2f}=0} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{200 \text{ k}} + \frac{1}{100 \text{ k}}$$

$$= 1.5 \times 10^{-5} \text{ S}$$

$$y_o = y_{22a} + y_{22f} = 1 \times 10^{-6} \text{ S} + 1 \times 10^{-5} \text{ S} = 1.1 \times 10^{-5} \text{ S}$$

$$y_{22a} = \frac{i_{2a}}{v_{2a}} \bigg|_{v_{1a}=0} = \frac{1}{R_o} = \frac{1}{1 \text{ M}} = 10^{-6} \text{ S}$$

$$y_{22f} = \frac{i_{2f}}{v_{2f}} \bigg|_{v_{1f}=0} = \frac{1}{R_2} = \frac{1}{100 \text{ k}} = 10^{-5} \text{ S}$$

$$y_{21a} = \frac{i_{2a}}{v_{1a}} \bigg|_{v_{2a}=0} = \frac{-a_v v_o}{R_o} = \frac{a_v}{R_o} = \frac{10^3}{1 \text{ M}} = 10^{-3} \text{ S}$$

$$y_{21f} = 0$$

$$a = -\frac{y_{21a} + y_{21f}}{y_i y_o} = -\frac{10^{-3} + 0}{3.5 \times 10^{-5} \times 1.1 \times 10^{-5}} = 2.6 \times 10^6 \Omega$$

$$f = y_{12a} + y_{12f} = 0 + 10^{-5} \text{ S} = 10^{-5} \text{ S}$$

$$y_{12a} = 0$$

$$y_{12f} = \frac{i_{1f}}{v_{2f}} \bigg|_{v_{1f}=0} = \frac{1}{R_2} = \frac{1}{100 \text{ k}} = 10^{-5} \text{ S}$$

$$a_f = 26$$

(c)

$$R = \frac{R_1 \parallel R_i}{R_o + R_2 + (R_1 \parallel R_i)} a_v = \frac{200 \text{ k} \parallel 50 \text{ k}}{1 \text{ M} + 100 \text{ k} + (200 \text{ k} \parallel 50 \text{ k})} 10^3 = 35$$

If v_i in Fig. 8.59 and i_i in Fig. 8.61 are disabled, the two circuits are the same, hence the same return ratio

(d)

Return ratios do not depend on feedback configurations, while loop gains do.

	Loop gain	Return ratio
Fig. 8.59	66	35
Fig. 8.61	26	35

CHAPTER 9

9.1

At low frequencies $T = af = 10$
where f is the feedback factor

$$T(jf) = \frac{10}{(1+j\frac{f}{f_1})(1+j\frac{f}{f_2})(1+j\frac{f}{f_3})}$$

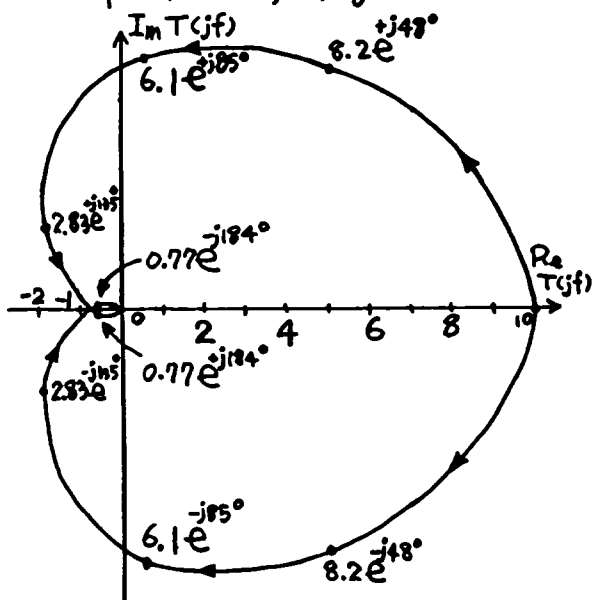
where f is the frequency

$$f = 1 \text{ MHz}$$

$$T(jf) = 6.1 e^{-95^\circ}$$

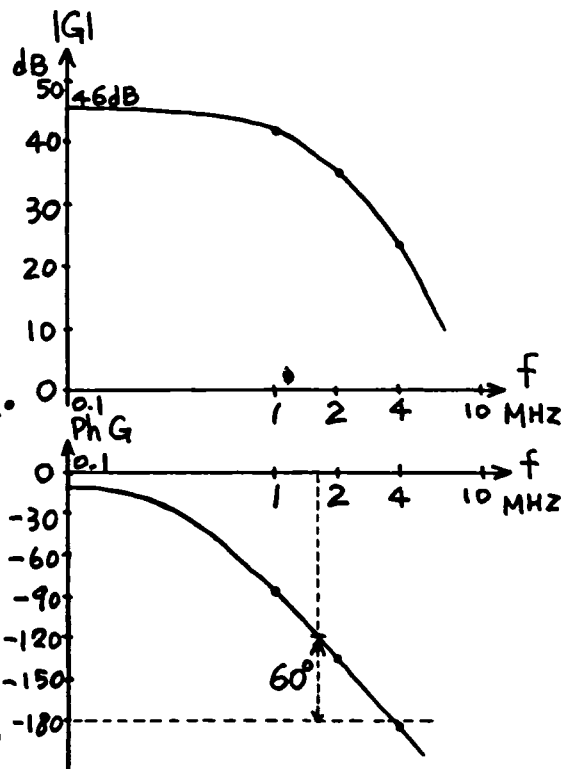
$$f = 2 \text{ MHz}, T(jf) = 2.83 e^{-135^\circ}$$

$$f = 4 \text{ MHz}, T(jf) = 0.77 e^{-184^\circ}$$



Does not encircle $(-1, 0)$

$\therefore$ Stable



$\text{Ph } G = -180^\circ$ at $f \approx 4 \text{ MHz}$

where $G = 23.8 \text{ dB} = 15.4$

$$\therefore f = \frac{1}{15.4} = 0.065$$

just causes instability

$\text{Ph } G = -120^\circ$, at $f = 1.7 \text{ MHz}$

where, $G = 71$

$$\therefore f = \frac{1}{71} = 0.014$$

gives 60° phase margin.

9.2

From 9.1

$$G(jf) = \frac{200}{(1+j\frac{f}{f_1})(1+j\frac{f}{f_2})(1+j\frac{f}{f_3})}$$

9.3

$$|T(j\omega)| = 1, \angle T(j\omega) = -160^\circ$$

$$\therefore A(j\omega) = \frac{a(j\omega)}{1 + T(j\omega)}$$

9-2

$$A(j\omega_0) = \frac{a(j\omega_0)}{1 + e^{-j160^\circ}} = \frac{a(j\omega_0)}{1 - 0.940 - 0.342j}$$

$$= \frac{a(j\omega_0)}{0.06 - 0.342j}$$

$$\text{But } |T(j\omega_0)| = |a(j\omega_0)f| = 1$$

$$\therefore |a(j\omega_0)| = \frac{1}{f}$$

$$\therefore |A(j\omega_0)| = \frac{2.88}{f}$$

$$= 20 \log_{10} \frac{1}{f} + 9.2 \text{ dB}$$

Thus the gain peaks 9.2 dB above the low-frequency value.

$$\therefore \text{At } 160 \text{ KHz}$$

$$|T(jf)| \approx 1, \angle T(jf) = -130^\circ$$

$$\therefore \text{Phase margin} = 50^\circ$$

(b)

$$A_0 = 200$$

$$\therefore T(jf) = \frac{200}{(1 + j\frac{f}{f_1})(1 + j\frac{f}{f_2})(1 + j\frac{f}{f_3})}$$

at 300 KHz

$$|T(jf)| = 0.74, \angle T(jf) = -150^\circ$$

at 250 KHz

$$|T(jf)| = 1, \angle T(jf) = -144^\circ$$

$$\therefore \text{Phase margin} = 36^\circ$$

$$A_0 = 100$$

$$\therefore T(jf) = \frac{400}{(1 + j\frac{f}{f_1})(1 + j\frac{f}{f_2})(1 + j\frac{f}{f_3})}$$

at 300 KHz

$$|T(jf)| = 1.48, \angle T(jf) = -150^\circ$$

at 350 KHz

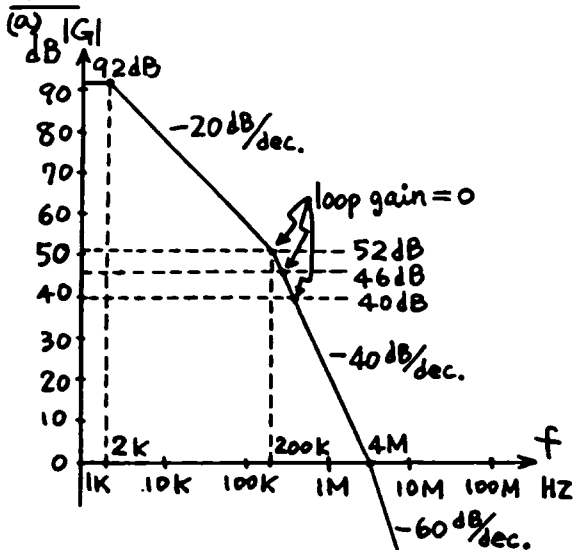
$$|T(jf)| = 1.13, \angle T(jf) = -155^\circ$$

at 375 KHz

$$|T(jf)| = 1, \angle T(jf) = -157^\circ$$

$$\therefore \text{Phase margin} = 23^\circ$$

9.4



Phase margin $\approx 45^\circ$

At 200 KHz

$$T(jf) = \frac{100}{(1 + j\frac{f}{f_1})(1 + j\frac{f}{f_2})(1 + j\frac{f}{f_3})}$$

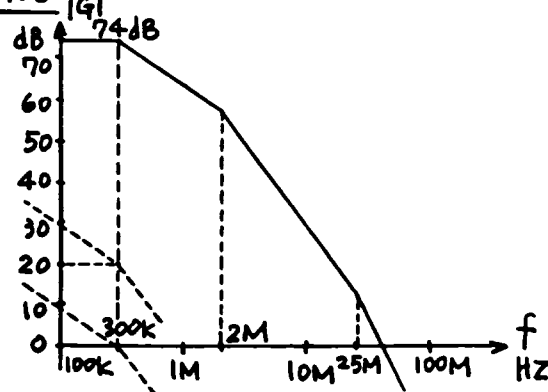
$$|T(jf)| = 0.706$$

$$\angle T(jf) = -137^\circ$$

At 150 KHz

$$|T(jf)| = 1.07, \angle T(jf) = -128^\circ$$

9.5



(a) Dominant pole = $\frac{300,000}{5000} = 60 \text{ Hz}$

Bandwidth of feedback circuit
 $\approx 300 \text{ KHz}$

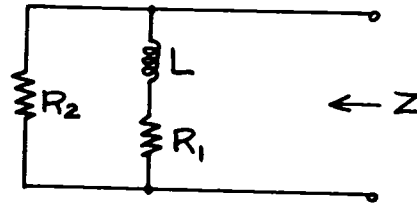
(b) Dominant pole = $\frac{300,000}{500} = 600 \text{ Hz}$

Bandwidth of feedback circuit
 $\approx 300 \text{ KHz}$

$$a_o = 100,000, \omega_1 = 5 \times 2\pi \text{ rad/sec}$$

$$\therefore Z_o = \frac{R_o}{1 + \frac{a_o f}{1 + \frac{s}{\omega_1}}} = \frac{R_o (1 + \frac{s}{\omega_1})}{1 + \frac{s}{\omega_1} + a_o f}$$

$$= \frac{R_o}{1 + a_o f} \frac{1 + \frac{s}{\omega_1}}{1 + \frac{s}{(1 + a_o f) \omega_1}} \quad \text{--- (A)}$$



$$Z = \frac{R_2(R_1 + Ls)}{R_1 + R_2 + Ls} = \frac{R_1 R_2}{R_1 + R_2} \frac{1 + \frac{L}{R_1} s}{1 + \frac{Ls}{R_1 + R_2}} \quad \text{--- (B)}$$

From (A) and (B)

$$\frac{R_1 R_2}{R_1 + R_2} = \frac{R_o}{1 + a_o f} = \frac{100}{1001} = 0.1 \Omega$$

$$\frac{L}{R_1} = \frac{1}{\omega_1}$$

$$\frac{L}{R_1 + R_2} = \frac{1}{(1 + a_o f) \omega_1}$$

$$\therefore \frac{R_1}{R_1 + R_2} = \frac{1}{1 + a_o f} = \frac{1}{1001}$$

$$\therefore R_2 = \frac{R_1 + R_2}{R_1} \times 0.1 \Omega = 100 \Omega$$

$$1 + \frac{R_2}{R_1} = 1001$$

$$\therefore R_2 = 1000 R_1$$

$$\therefore R_1 = 0.1 \Omega$$

$$L = \frac{1}{\omega_1} R_1$$

$$= \frac{1}{5 \times 2\pi} \times 0.1$$

$$= 3.18 \text{ mH}$$

9.6

(a) Dominant pole = $\frac{2 \text{ MHz}}{5000} = 400 \text{ Hz}$

Bandwidth of feedback circuit
 $\approx 400 \times 5000 = 2 \text{ MHz}$

(b) Dominant pole = $\frac{2 \text{ MHz}}{500} = 4 \text{ KHz}$

Bandwidth of feedback $\approx 2 \text{ MHz}$

9.7

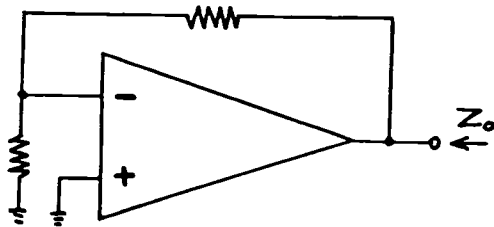
(a) Dominant pole = $\frac{200 \text{ KHz}}{40,000} = 5 \text{ Hz}$

Bandwidth of feedback circuit
 $\approx 200 \text{ KHz}$

(b) Dominant pole = $\frac{200 \text{ KHz}}{4000} = 50 \text{ Hz}$

Bandwidth $\approx 200 \text{ KHz}$

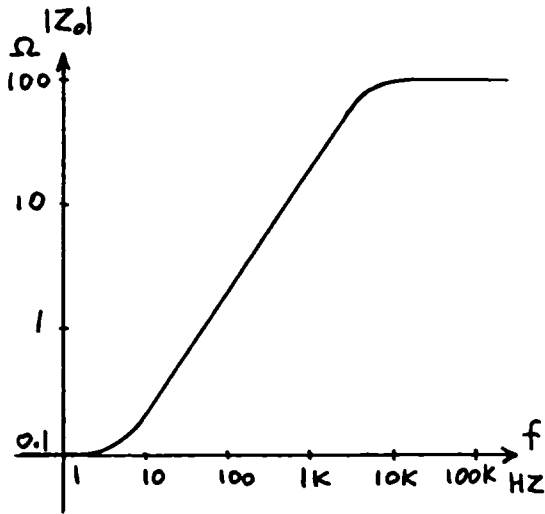
9.8



$$Z_o = \frac{R_o}{1 + T(s)} = \frac{R_o}{1 + a f}$$

$$f = 0.01, a = \frac{a_o}{1 + \frac{s}{\omega_1}}$$

9-4



Try $f_1 = 30 \text{ Hz}$

By trial

$|a| = 1$ at $f = 6.5 \text{ MHz}$

where $\angle a = -123^\circ$

$\rightarrow$ Phase margin $= 57^\circ$

Try $f_1 = 25 \text{ Hz}$

By trial

$|a| = 1$ at $f = 5.5 \text{ MHz}$

where $\angle a = -119^\circ$

$\rightarrow$ Phase margin $= 61^\circ$

By interpolation we need

$f_1 = 26 \text{ Hz}$, giving a unity gain frequency of 5.7 MHz

From Chapter 7

$$f_1 = \frac{1}{2\pi C_M R_{ic}}$$

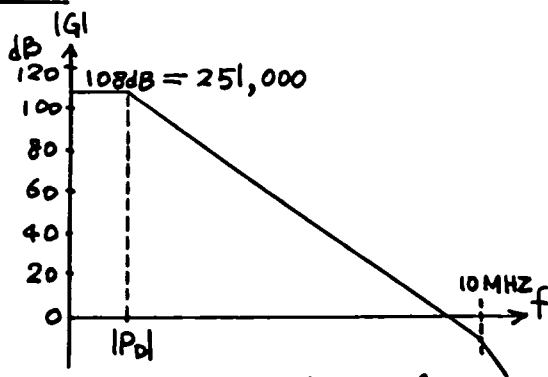
$$\text{where } C_M = (1 + G_m R_{oc}) C_c = 552 C_c$$

$$\text{and } R_{ic} = 1.95 \times 10^6$$

$$\therefore 26 = \frac{1}{2\pi \cdot 552 C_c \cdot 1.95 \times 10^6}$$

$$\therefore C_c = 5.7 \text{ pF}$$

9.9



Calculate dominant pole freq. required

$$|P_D| < \frac{10 \text{ MHz}}{251,000} = 40 \text{ Hz}$$

When compensated

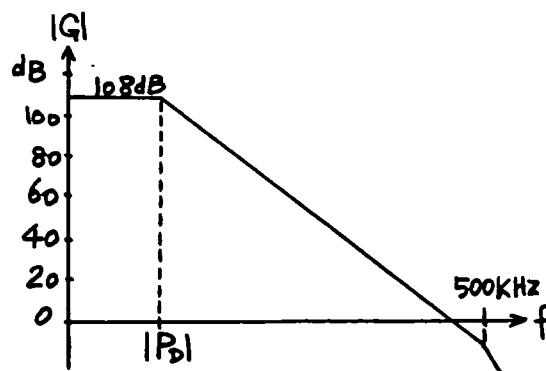
$$a = \frac{251,000}{(1 + j \frac{f}{f_1})(1 + j \frac{f}{f_2})}$$

$$f_2 = 10 \text{ MHz}, f_1 = |P_D|$$

at the unity gain frequency

$$a \approx \frac{251,000}{j \frac{f}{f_1} (1 + j \frac{f}{f_2})}$$

9.10



Dominant pole freq. required

$$|P_D| < \frac{500 \text{ kHz}}{251,000} = 2 \text{ Hz}$$

when compensated

$$a = \frac{251,000}{(1+j\frac{f}{f_1})(1+j\frac{f}{f_2})}$$

$$f_2 = 500 \text{ KHz}, f_1 = 1 \text{ P}_0$$

at the unity gain frequency

$$a \approx \frac{251,000}{j\frac{f}{f_1}(1+j\frac{f}{f_2})}$$

From problem 9.9, we found for 60° phase margin that

$$\frac{f_2}{f_1} = \frac{10 \text{ MHz}}{26 \text{ Hz}} = 3.85 \times 10^5$$

$\therefore$ we now need

$$f_1 = \frac{500 \text{ KHz}}{3.85 \times 10^5} = 1.3 \text{ Hz}$$

In problem 9.9 unity gain freq. = 5.7 MHz

$$\therefore \text{In this case unity gain freq.} = \frac{5.7 \text{ MHz}}{20} = 285 \text{ KHz}$$

From Section (9.4) for this compensation

$$f_1 = \frac{1}{2\pi RC}$$

$$\therefore 1.3 = \frac{1}{2\pi \times 1.95 \times 10^6 \times C}$$

$$\therefore C = 0.063 \mu\text{F}$$

9.11

Breakaway between P_1 and P_2

$$\frac{1}{\sigma_i + 1} + \frac{1}{\sigma_i + 3} + \frac{1}{\sigma_i + 4} = 0$$

$$\therefore (\sigma_i + 3)(\sigma_i + 4) + (\sigma_i + 1)(\sigma_i + 4) + (\sigma_i + 1)(\sigma_i + 3) = 0$$

$$\therefore 3\sigma_i^2 + 16\sigma_i + 19 = 0$$

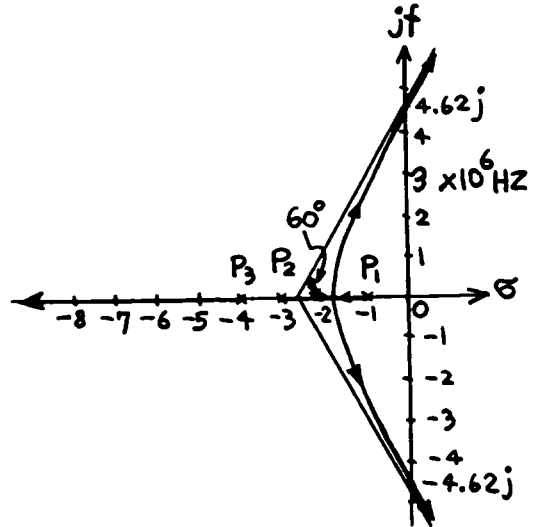
$$\therefore \sigma_i = \frac{-16 \pm \sqrt{16^2 - 12 \times 19}}{6} = -1.78 \text{ or } -3.55$$

$$\therefore \sigma_i = -1.78$$

Angle of asymptotes to axis = 60°

Asymptotes meet real axis at

$$\sigma_a = \frac{-1-3-4+0}{3} = -2.67$$



Root locus crosses axis at $s = j4.62$ (normalized to 10^6 Hz)

Then

$$|s - P_1| = 4.73,$$

$$|s - P_2| = 5.51,$$

$$|s - P_3| = 6.11.$$

Using (9.60)

$$T_o \times \frac{1 \times 3 \times 4}{4.73 \times 5.51 \times 6.11} = 1$$

$$\therefore T_o = 13.3$$

Since $a_o = 200$, we have

$$f = \frac{13.3}{200} = 0.067$$

for instability.

9.12

Breakaway point between P_1 and P_2

$$\frac{1}{\sigma_i + 2} + \frac{1}{\sigma_i + 200} + \frac{1}{\sigma_i + 4000} = 0$$

↑ neglect

$$\therefore \sigma_i + 200 + \sigma_i + 2 = 0$$

$$\therefore \sigma_i = -101$$

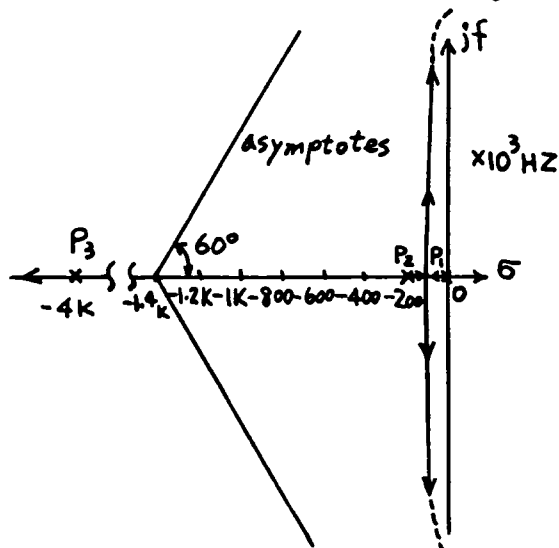
Angle of asymptotes to axis = 60°

Asymptotes meet real axis at

$$\sigma_a = \frac{-2 - 200 - 4000}{3} = -1400$$

Root locus crosses axis at

$$s = 1400 \tan 60^\circ j = 2425j$$



$$\text{Then } |s - P_1| = 2425,$$

$$|s - P_2| = 2433, |s - P_3| = 4677$$

Using (9.60)

$$T_o \times \frac{2 \times 200 \times 4000}{2425 \times 2433 \times 4677} = 1$$

$$\therefore T_o = 17,250$$

Since $a_o = 40,000$ the value of f causing instability is

$$40,000 f = 17,250$$

$$\therefore f = 0.43$$

Using Nyquist calculate $T(j\omega)$

$$T(jf) = \frac{17,250}{(1+j\frac{f}{2})(1+j\frac{f}{200})(1+j\frac{f}{4000})}$$

$$\text{Put } f = 2425$$

$$|T(jf)| = 1, \angle T(jf) = -206^\circ$$

Unstable, but since $\angle T(jf)$ is less than -180° , the circuit would be unstable for smaller values of f .

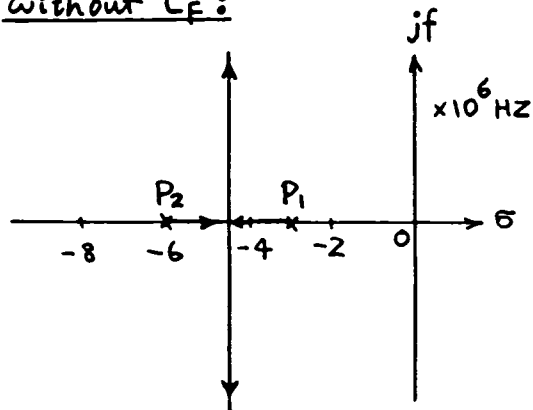
9.13

$$\text{Zero freq. } \omega_z = \frac{1}{R_F C_F}$$

$$= \frac{1}{5000 \times 1.5 \times 10^{-12}}$$

$$= 1.33 \times 10^8 \text{ rad/sec}$$

$$\therefore f_z = 21.2 \text{ MHz}$$

without C_F :

$$A = \frac{a}{1+af}$$

$$a = \frac{a_o}{(1-\frac{s}{P_1})(1-\frac{s}{P_2})}$$

$$= \frac{a_o}{(1-\frac{s}{P_1})(1-\frac{s}{P_2}) + a_o f}$$

For $f = 0.01$, $a_o f = 40$

and poles are

9-7

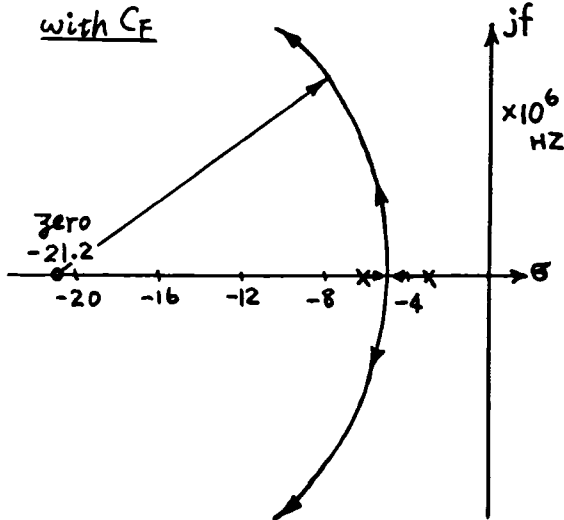
$$(1 + \frac{s}{3})(1 + \frac{s}{6}) + 40 = 0$$

$$\therefore s^2 + 9s + 738 = 0$$

$$\therefore s = \frac{-9 \pm \sqrt{81 - 4 \times 738}}{2}$$

$$= -4.5 \pm j26.8$$

$\therefore$ for $f = 0.01$, poles P_a and P_b are at $(-4.5 \pm j26.8)$ MHz with C_F



Breakaway point

$$\frac{1}{\sigma_i + 3} + \frac{1}{\sigma_i + 6} = \frac{1}{\sigma_i + 21.2}$$

$\therefore \sigma_i \approx -4.5$ as for previous case.

$$A = \frac{a}{1 + af} \quad a = \frac{a_0}{(1 - \frac{s}{P_1})(1 - \frac{s}{P_2})}$$

$$f = f_0 (1 - \frac{s}{Z})$$

$$\therefore A = \frac{a_0}{(1 - \frac{s}{P_1})(1 - \frac{s}{P_2}) + a_0 f_0 (1 - \frac{s}{Z})}$$

For $f_0 = 0.01$, $a_0 f_0 = 40$

and poles are

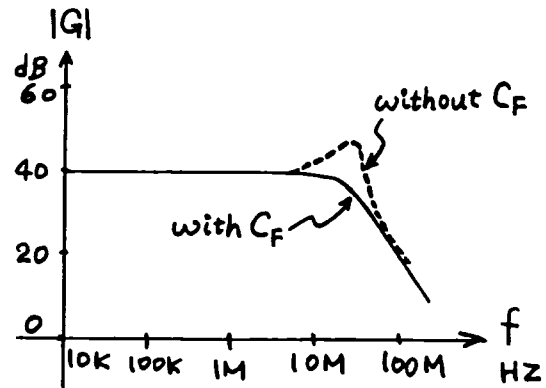
$$(1 + \frac{s}{3})(1 + \frac{s}{6}) + 40(1 + \frac{s}{21.2}) = 0$$

$$\therefore s^2 + 43s + 738 = 0$$

$$\therefore s = \frac{-43 \pm \sqrt{43^2 - 4 \times 738}}{2}$$

$$= -21.5 \pm j16.6$$

$\therefore$ poles P_a and P_b are at $(-21.5 \pm j16.6)$ MHz

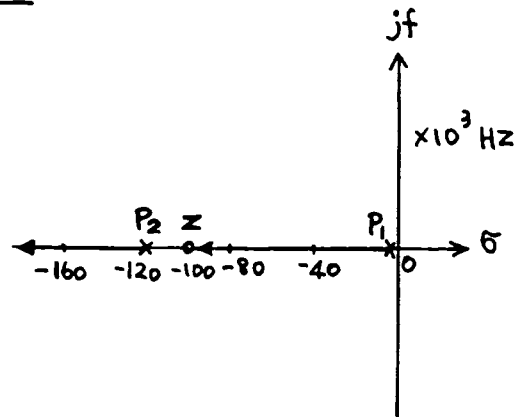


For the feedback amplifier

$$G = \frac{100}{(1 - \frac{s}{P_a})(1 - \frac{s}{P_b})}$$

where P_a and P_b are calculated above.

9.14



$$A(s) = \frac{a(s)}{1 + af(s)}$$

$$a(s) = \frac{a_0(1 - \frac{s}{Z})}{(1 - \frac{s}{P_1})(1 - \frac{s}{P_2})}$$

9.15

$$\therefore A(s) = \frac{a_0(1 - \frac{s}{Z})}{(1 - \frac{s}{P_1})(1 - \frac{s}{P_2}) + a_0 f (1 - \frac{s}{Z})}$$

Poles are the solutions of

$$(1 - \frac{s}{P_1})(1 - \frac{s}{P_2}) + a_0 f (1 - \frac{s}{Z}) = 0$$

$$\therefore 1 - (\frac{1}{P_1} + \frac{1}{P_2} + \frac{a_0 f}{Z})s + \frac{s^2}{P_1 P_2} + a_0 f = 0$$

$$\therefore s^2 - P_1 P_2 (\frac{1}{P_1} + \frac{1}{P_2} + \frac{a_0 f}{Z})s + P_1 P_2 (1 + a_0 f) = 0$$

Normalized to KHZ

$$\therefore P_1 = -0.1, P_2 = -120$$

$$Z = -100, a_0 = 10^5$$

$$f = 10^{-3}$$

$$s^2 - 12(-10 - \frac{1}{120} - \frac{100}{100})s + 12 \times 101 = 0$$

$$\therefore s^2 + 132s + 1212 = 0$$

$$\therefore s = \frac{-132 \pm \sqrt{132^2 - 4 \times 1212}}{2}$$

$$= -66 \pm 56 = -10 \text{ or } -122$$

$\therefore$ Poles are at -10 KHZ and -122 KHZ

Zero is at -100 KHZ

$$f = 1$$

$$s^2 - 12(-10 - \frac{1}{120} - \frac{10^5}{100})s + 12 \times 10^5 = 0$$

$$\therefore s^2 + 12120s + 12 \times 10^5 = 0$$

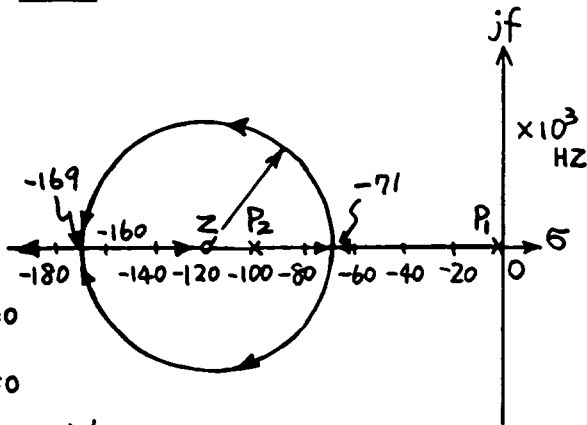
$$\therefore s = \frac{-12120 \pm \sqrt{12120^2 - 12 \times 10^5 \times 4}}{2}$$

$$= -6060 \pm 5960.2$$

$$= -99.8 \text{ or } -12020$$

$\therefore$ Poles are at -99.8 KHZ and -12 MHz

Zero is at -100 KHZ



Normalize to KHZ

Breakaway point

$$\frac{1}{\sigma_i + 0.1} + \frac{1}{\sigma_i + 100} = \frac{1}{\sigma_i + 120}$$

$$\therefore (\sigma_i + 100)(\sigma_i + 120) + (\sigma_i + 0.1)(\sigma_i + 120) = (\sigma_i + 0.1)(\sigma_i + 100)$$

$$\therefore \sigma_i^2 + 240\sigma_i + 12002 = 0$$

$$\therefore \sigma_i = \frac{-240 \pm \sqrt{240^2 - 4 \times 12002}}{2}$$

$$= -120 \pm 49$$

$$= -169 \text{ or } -71$$

From 9.14 poles of feedback amplifier are given by solutions of

$$s^2 - P_1 P_2 (\frac{1}{P_1} + \frac{1}{P_2} + \frac{a_0 f}{Z})s + P_1 P_2 (1 + a_0 f) = 0$$

$$\therefore P_1 = -0.1, P_2 = -100, Z = -120$$

$$a_0 = 10^5$$

$$f = 10^{-3}$$

$$s^2 - 10(-10 - \frac{1}{100} - \frac{100}{120})s + 10 \times 101 = 0$$

$$\therefore s^2 + 108.4s + 1010 = 0$$

$$\therefore s = \frac{-108.4 \pm \sqrt{108.4^2 - 4040}}{2}$$

$$= -98.1 \text{ or } -10.3$$

9-9

$\therefore$ Poles are at -10.3 kHz and -98.1 kHz

Zero is at -120 kHz

$f=1$

$$s^2 - 10(-10 - \frac{1}{100} - \frac{10^5}{120})s + 10 \times 10^5 = 0$$

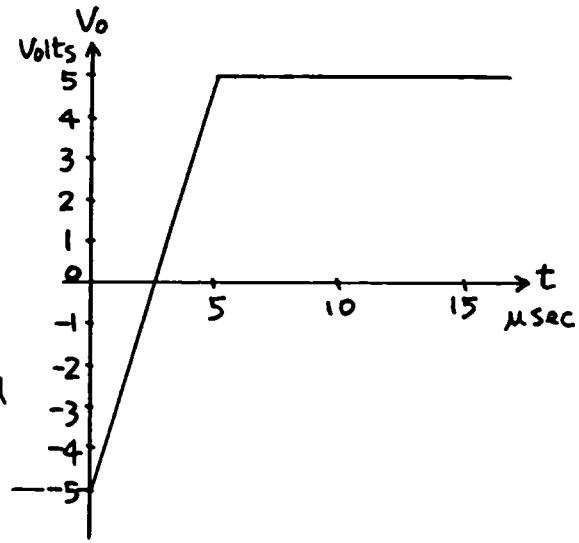
$$\therefore s^2 + 8433s + 10^6 = 0$$

$$\therefore s = -4216.5 \pm 4096$$

$$= -8313 \text{ or } -120.5$$

$\therefore$ Poles are at -120.5 kHz and -8.3 MHz

Zero is at -120 kHz



9.16

$$(a) \frac{\Delta V_o}{\Delta V_i}(j\omega) \approx -G_m \frac{1}{j\omega C}$$

at high frequencies where

$$G_m = g_{m1} = \frac{I_{C1}}{V_T} = \frac{10 \times 10^{-6}}{26 \times 10^{-3}} \text{ A/V}$$

$$C = 10 \text{ pF}$$

$\therefore$ unity gain frequency ω_o is given by

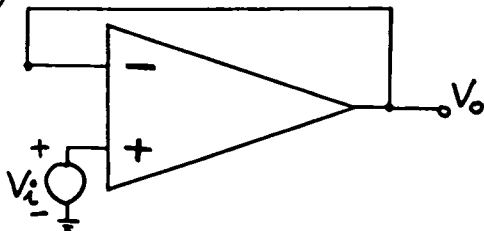
$$G_m \frac{1}{\omega_o C} = 1$$

$$\therefore \omega_o = \frac{G_m}{C} = \frac{10^{-5}}{26 \times 10^{-3}} \frac{10^{12}}{10}$$

$$\therefore f_o = 6.12 \text{ MHz}$$

$$\text{Slew rate} = \frac{2I_{C1}}{C} = \frac{20 \times 10^{-6}}{10 \times 10^{-12}} \\ = 2 \text{ V}/\mu\text{s}$$

(b)



```

OP AMP
VCC 1 0 15V
VSS 2 0 -15V
IKK 1 9 200A
Q1 5 3 9 P
Q2 6 4 9 P
Q3 5 5 2 M
Q4 6 5 2 M
Q5 1 6 7 M
RES 7 2 50K
Q6 8 7 2 M
I6 1 8 300U
CCOMP 6 8 10P
VIN2 4 0 0V
VIN 3 0 0V AC
.MODEL N NPN BF=100 VAF=130 IS=1E-15
.MODEL P PNP BF=100 VAF=130 IS=1E-15
.PLOT AC V(8)
.AC DEC 40 LIN 10MEG
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.END

```

***** AC ANALYSIS THOM= 27.000 TEMP= 27.000

TIME	V(8)				
(A)		0.	2.000E+00	4.000E+00	6.000E+00
2.985E+06	2.02E+00	+	A	+	+
1.162E+06	1.91E+00	+	A	+	+
3.349E+06	1.80E+00	+	A	+	+
3.548E+06	1.70E+00	+	A	+	+
3.750E+06	1.61E+00	+	A	+	+
3.981E+06	1.52E+00	+	A	+	+
4.217E+06	1.43E+00	+	A	+	+
4.466E+06	1.35E+00	+	A	+	+
4.731E+06	1.27E+00	+	A	+	+
5.011E+06	1.20E+00	+	A	+	+
5.308E+06	1.14E+00	+	A	+	+
5.623E+06	1.07E+00	+	A	+	+
5.956E+06	1.01E+00	+	A	+	+
6.309E+06	9.60E-01	+	A	+	+
6.683E+06	9.06E-01	+	A	+	+
7.079E+06	8.55E-01	+	A	+	+
7.498E+06	8.08E-01	+	A	+	+

UNITY GAIN FREQUENCY = 6 MEGAHERTZ

```

OP AMP
VCC 1 0 15V
VSS 2 0 -15V
IKK 1 9 200A
Q1 5 3 9 P
Q2 6 4 9 P
Q3 5 5 2 M
Q4 6 5 2 M
Q5 1 6 7 M
RES 7 2 50K
Q6 8 7 2 M
I6 1 8 300U
CCOMP 6 8 10P
VIN 4 0 PULSE -5 5 0 0 0 30US
.MODEL N NPN BF=100 VAF=130 IS=1E-15
.MODEL P PNP BF=100 VAF=130 IS=1E-15
.PLOT TRAN V(8)
.TRAN 0.25U 10U
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

```

+0:1 = 1.500E+01 0:2 = -1.500E+01 0:4 = -5.000E+00
+0:5 = -1.440E+01 0:6 = -1.371E+01 0:7 = -1.431E+01
+0:8 = -4.999E+00 0:9 = -4.406E+00

```

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	Q:Q1	Q:Q2	Q:Q3	Q:Q4	Q:Q5	Q:Q6
MODEL	Q:P	Q:P	Q:N	Q:N	Q:N	Q:M
IB	-9.243E-08	-9.281E-08	9.718E-08	9.718E-08	1.335E-07	2.800E-06
IC	-9.912E-06	-9.903E-06	9.718E-06	9.769E-06	1.630E-05	3.001E-04
VBE	-5.935E-01	-5.936E-01	5.948E-01	5.948E-01	6.030E-01	6.817E-01
VCE	-9.998E+00	-9.308E+00	5.948E-01	1.284E+00	2.931E+01	1.000E+01
VBC	9.405E+00	8.715E+00	0.	-6.899E-01	-2.871E+01	-9.318E+00
VS	4.999E+00	5.000E+00	1.440E+01	1.371E+01	-1.500E+01	4.999E+00
POWER	9.916E-05	9.224E-05	5.838E-06	1.261E-05	4.780E-04	3.003E-03
RETD	1.072E+02	1.067E+02	1.000E+02	1.005E+02	1.220E+02	1.071E+02
GM	3.832E-04	3.828E-04	3.756E-04	3.776E-04	6.302E-04	1.160E-02
XPI	2.798E+05	2.786E+05	2.661E+05	2.661E+05	1.937E+05	9.236E+03
RX	0.	0.	0.	0.	0.	0.
RO	1.406E+07	1.400E+07	1.337E+07	1.337E+07	9.736E+06	4.642E+05
CPI	0.	0.	0.	0.	0.	0.
CMU	0.	0.	0.	0.	0.	0.
CRX	0.	0.	0.	0.	0.	0.
CCS	0.	0.	0.	0.	0.	0.
RETLAC	1.072E+02	1.066E+02	9.998E+01	1.005E+02	1.220E+02	1.071E+02
FT	6.098E+10	6.092E+10	5.978E+10	6.010E+10	1.002E+11	1.846E+12

***** TRANSIENT ANALYSIS THOM= 27.000 TEMP= 27.000

TIME	V(8)				
(A)		-5.000E+00	0.	5.000E+00	1.000E+01
0.	-5.00E+00	+	+	+	+
2.500E-07	-4.51E+00	+	+	+	+
5.000E-07	-4.01E+00	+	+	+	+
7.500E-07	-3.52E+00	+	+	+	+
1.000E-06	-3.03E+00	+	+	+	+
1.250E-06	-2.54E+00	+	+	+	+
1.500E-06	-2.05E+00	+	+	+	+
1.750E-06	-1.56E+00	+	+	+	+
2.000E-06	-1.07E+00	+	+	+	+
2.250E-06	-5.79E-01	+	+	+	+
2.500E-06	-8.78E-02	+	+	+	+
2.750E-06	4.04E-01	+	+	+	+
3.000E-06	8.95E-01	+	+	+	+
3.250E-06	1.38E+00	+	+	+	+
3.500E-06	1.87E+00	+	+	+	+
3.750E-06	2.37E+00	+	+	+	+
4.000E-06	2.86E+00	+	+	+	+
4.250E-06	3.35E+00	+	+	+	+
4.500E-06	3.84E+00	+	+	+	+
4.750E-06	4.33E+00	+	+	+	+
5.000E-06	4.82E+00	+	+	+	+
5.250E-06	5.00E+00	+	+	+	+
5.500E-06	5.00E+00	+	+	+	+
5.750E-06	5.00E+00	+	+	+	+
6.000E-06	5.00E+00	+	+	+	+
6.250E-06	5.00E+00	+	+	+	+
6.500E-06	5.00E+00	+	+	+	+
6.750E-06	5.00E+00	+	+	+	+
7.000E-06	5.00E+00	+	+	+	+
7.250E-06	5.00E+00	+	+	+	+
7.500E-06	5.00E+00	+	+	+	+
7.750E-06	5.00E+00	+	+	+	+
8.000E-06	5.00E+00	+	+	+	+
8.250E-06	5.00E+00	+	+	+	+
8.500E-06	5.00E+00	+	+	+	+
8.750E-06	5.00E+00	+	+	+	+
9.000E-06	5.00E+00	+	+	+	+
9.250E-06	5.00E+00	+	+	+	+
9.500E-06	5.00E+00	+	+	+	+
9.750E-06	5.00E+00	+	+	+	+
1.000E-05	5.00E+00	+	+	+	+

SLEW RATE = 10V/5.25US = 1.9V/US

9.17

$$(a) \frac{\Delta V_o}{\Delta V_i}(j\omega) \approx -G_m \frac{1}{j\omega C} A_v$$

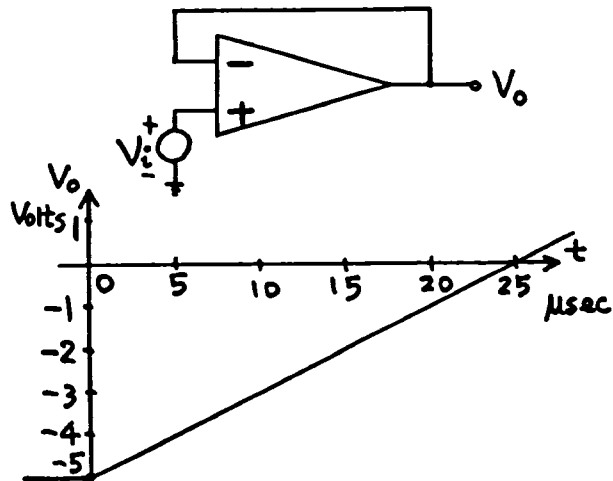
where $A_v = 500$, $C = 0.05 \mu F$

$$\therefore 1 = \frac{10^{-5}}{26 \times 10^{-3}} \frac{10^6}{\omega_0 \times 0.05} \times 500$$

$$\therefore f_0 = 612 \text{ KHz}$$

$$\text{Slew rate} = \frac{2 I_{c1}}{C} A_v$$

$$= \frac{20 \times 10^{-6}}{0.05 \times 10^{-6}} \times 500 = 0.2 \text{ V}/\mu\text{s}$$



9-11

9.18

$$\frac{\Delta V_o}{\Delta V_i}(j\omega) = -G_m \frac{1}{j\omega C}$$

where $G_m = \frac{g_{m1}}{1 + g_{m1} R_E}$

$$= \frac{g_{m1}}{1 + \frac{10^{-5}}{26 \times 10^{-3}} \times 10^4} = \frac{g_{m1}}{4.85}$$

For same unity gain freq.

$$C = \frac{10}{4.85} \text{ PF} = 2.06 \text{ PF}$$

$$\text{Slew rate} = \frac{2 I_{C1}}{C}$$

$$= \frac{20 \times 10^{-6}}{2.06 \times 10^{-12}} = 9.7 \text{ V}/\mu\text{s}$$

Slew rate improves by a factor 4.85

OP AMP WITH EMITTER-DEGENERATED INPUT STAGE

```
VCC 1 0 15V
VSS 2 0 -15V
IEE 1 9 20UA
RE1 9 13 10K
RE2 9 14 10K
Q1 5 3 13 P
Q2 6 4 14 P
Q3 5 5 2 N
Q4 6 5 2 N
Q5 1 6 7 N
RES 7 2 50K
Q6 8 7 2 N
I6 1 8 300U
CCOMP 6 8 2.06P
VIN2 3 0 0V
VIN 4 0 0V AC
.MODEL N NPN BF=100 VAF=130 IS=1E-15
.MODEL P PNP BF=100 VAF=130 IS=1E-15
.PLOT AC V(8)
.AC DEC 40 1MEG 10MEG
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.END
```

***** AC ANALYSIS TNUM= 27.000 TEMP= 27.000

FREQ	V(8)				
A	0.	2.000E+00	4.000E+00	6.000E+00	8.000E+00
1.778E+05	3.39E+00	-A			
1.889E+05	3.10E+00	+A			
1.995E+05	3.02E+00	+A			
2.113E+05	2.85E+00	+A			
2.238E+05	2.69E+00	+A			
2.371E+05	2.54E+00	+A			
2.511E+05	2.40E+00	+A			
2.660E+05	2.26E+00	+A			
2.818E+05	2.14E+00	-A			
2.985E+05	2.02E+00	-A			
3.162E+05	1.90E+00	-A			
3.349E+05	1.80E+00	-A			
3.548E+05	1.70E+00	-A			
3.759E+05	1.60E+00	-A			
3.981E+05	1.51E+00	-A			
4.217E+05	1.43E+00	-A			
4.466E+05	1.35E+00	-A			
4.731E+05	1.27E+00	-A			
5.011E+05	1.20E+00	-A			
5.308E+05	1.13E+00	-A			
5.623E+05	1.07E+00	-A			
5.956E+05	1.01E+00	-A			
6.309E+05	9.57E-01	-A			
6.683E+05	9.03E-01	-A			
7.079E+05	8.53E-01	-A			
7.498E+05	8.05E-01	-A			

UNITY GAIN FREQUENCY = 6 MEGAHERTZ

OP AMP WITH EMITTER-DEGENERATED INPUT STAGE

```
VCC 1 0 15V
VSS 2 0 -15V
IEE 1 9 20UA
RE1 9 13 10K
RE2 9 14 10K
Q1 5 3 13 P
Q2 6 4 14 P
Q3 5 5 2 N
Q4 6 5 2 N
Q5 1 6 7 N
RES 7 2 50K
Q6 8 7 2 N
I6 1 8 300U
CCOMP 6 8 2.06P
VIN 4 0 PULSE -5 5 0 0 30US
.MODEL N NPN BF=100 VAF=130 IS=1E-15
.MODEL P PNP BF=100 VAF=130 IS=1E-15
.PLOT TRAN V(8)
.TRAN 0.05U 1.8U
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.END
```

***** OPERATING POINT INFORMATION TNUM= 27.000 TEMP= 27.000

```
+0:1 = 1.500E+01 0:2 = -1.500E+01 0:4 = -5.000E+00
+0:5 = -1.440E+01 0:6 = -1.371E+01 0:7 = -1.431E+01
+0:8 = -5.000E+00 0:9 = -4.306E+00 0:13 = -4.406E+00
+0:14 = -4.406E+00
```

***** TRANSIENT ANALYSIS TNUM= 27.000 TEMP= 27.000

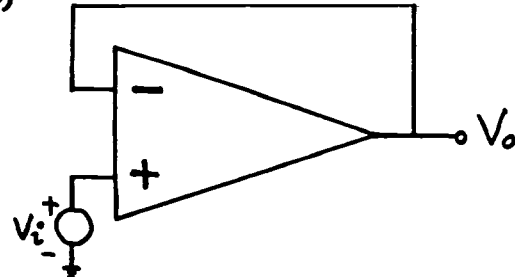
TIME	V(8)				
(A)	-1.000E+01	-5.000E+00	0.	5.000E+00	1.000E+01
0.	-5.00E+00	-A			
5.000E-08	-4.52E+00	+A			
1.000E-07	-4.04E+00	+A			
1.500E-07	-3.57E+00	+A			
2.000E-07	-3.09E+00	+A			
2.500E-07	-2.61E+00	+A			
3.000E-07	-2.14E+00	-A			
3.500E-07	-1.66E+00	+A			
4.000E-07	-1.18E+00	-A			
4.500E-07	-7.08E-01	+A			
5.000E-07	-2.31E-01	-A			
5.500E-07	2.46E-01	-A			
6.000E-07	7.23E-01	+A			
6.500E-07	1.20E+00	+A			
7.000E-07	1.67E+00	+A			
7.500E-07	2.15E+00	+A			
8.000E-07	2.63E+00	+A			
8.500E-07	3.10E+00	+A			
9.00E-07	3.58E+00	+A			
9.50E-07	4.06E+00	+A			
1.000E-06	4.54E+00	-A			
1.050E-06	4.90E+00	-A			
1.100E-06	4.98E+00	-A			
1.150E-06	4.99E+00	-A			
1.200E-06	5.00E+00	-A			
1.250E-06	5.00E+00	-A			
1.300E-06	5.00E+00	-A			
1.350E-06	5.00E+00	-A			
1.400E-06	5.00E+00	-A			
1.450E-06	5.00E+00	-A			
1.500E-06	5.00E+00	-A			
1.550E-06	5.00E+00	-A			
1.600E-06	5.00E+00	-A			
1.650E-06	5.00E+00	-A			
1.700E-06	5.00E+00	-A			
1.750E-06	5.00E+00	-A			
1.800E-06	5.00E+00	-A			

SLEW RATE = 10V/1.2US = 8.33V/US
8.33/1.9 = 4.4 IMPROVEMENT

9-12

is the full-power bandwidth.

(b)



$$V_i = 10 \sin 2\pi f t$$

where $f = 45 \text{ KHz}$

$$\frac{dV_i}{dt} = 2\pi f \times 10 \cos 2\pi f t$$

$$= 2.83 \times 10^6 \cos 2\pi f t$$

To find point of slew limiting
put $\frac{dV_i}{dt} = 2 \times 10^6 \text{ V/s}$

$$\therefore 2 \times 10^6 = 2.83 \times 10^6 \cos 2\pi f t$$

$$\therefore \cos 2\pi f t = 0.707$$

$$\therefore 2\pi f t = 0.786$$

$$\therefore t = 2.8 \mu\text{s}$$

9.19

$$G_m = 0.3 \text{ mA/V}$$

$$\frac{\Delta V_o}{\Delta V_i}(j\omega) = -G_m \frac{1}{j\omega C}$$

$$\therefore | | = 0.3 \times 10^3 \frac{1}{6.12 \times 10^6 \times 2\pi \times C}$$

$$\therefore C = 7.8 \text{ pF}$$

$$\text{Slew Rate} = \frac{2 I_{C1}}{C}$$

$$= \frac{600 \times 10^{-6}}{7.8 \times 10^{-12}} = 77 \text{ V}/\mu\text{s}$$

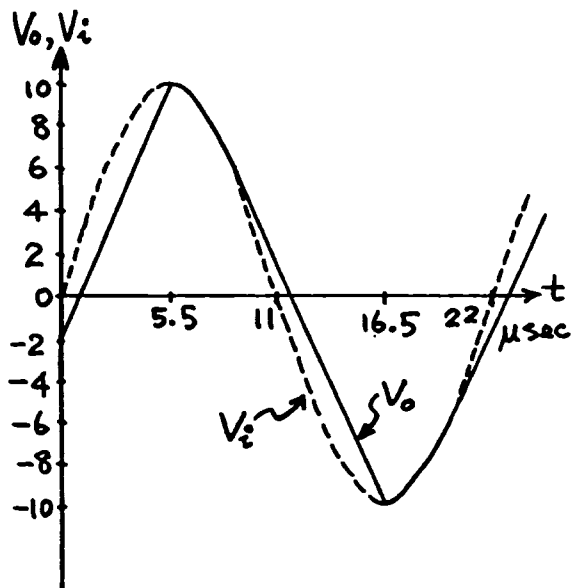
Slew rate improves 38 times

9.20

$$(a) \left. \frac{dV_i}{dt} \right|_{\text{MAX}} = \omega V_M$$

$$\therefore \omega = \frac{2 \text{ V}/\mu\text{s}}{15 \text{ V}} = 133 \times 10^3 \text{ rad/sec}$$

$$\therefore f = 21.2 \text{ KHz}$$



9.21

$$L_{eff} = L - 2L_d - X_d$$

$$= 8 - 2(0.3) - 1 = 6.4 \mu$$

$$I_D = 20 \mu A \text{ for } m_8, m_5, m_7, m_6$$

$$I_D = 10 \mu A \text{ for } m_1, m_2, m_3, m_4$$

$$\frac{1}{r_o} = \frac{\partial I_D}{\partial V_{DS}} = \frac{I_D}{L_{eff}} \frac{\partial X_d}{\partial V_{DS}}$$

$$nmos \quad \frac{\partial X_d}{\partial V_{DS}} = 0.2 \frac{\mu}{V}$$

$$pmos \quad \frac{\partial X_d}{\partial V_{DS}} = 0.1 \frac{\mu}{V}$$

$$\frac{1}{r_{o2}} = \frac{10 \mu}{6.4 \mu} \cdot 0.1 \mu = 156 n$$

$$\frac{1}{r_{o4}} = \frac{10 \mu}{6.4 \mu} \cdot 0.2 \mu = 313 n$$

$$g_{m2} = \sqrt{2 k_p' \frac{W}{L_{eff}} I_D}$$

$$= \sqrt{2 (30.2 \mu) \frac{100 \mu}{6.4 \mu} 10 \mu}$$

$$= 97.1 \mu$$

$$k_p' = \mu_p C_{ox}$$

$$= 350 \frac{cm^2}{Vs} \cdot 86.3 \times 10^{-9} \frac{F}{cm^2}$$

$$= 30.2 \times 10^{-6} \frac{C}{V^2 s}$$

$$= 30.2 \mu \frac{A}{V^2}$$

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{\epsilon_r \epsilon_0}{t_{ox}}$$

$$= \frac{3.9 (8.85 \times 10^{-14} \frac{F}{cm})}{40 \times 10^{-7} cm}$$

$$= 86.3 \times 10^{-9} \frac{F}{cm^2}$$

$$g_{m6} = \sqrt{2 k_n' \frac{W}{L_{eff}} I_D}$$

$$= \sqrt{2 (60.4 \mu) \frac{100}{6.4} 20 \mu}$$

$$= 194 \mu$$

9-13

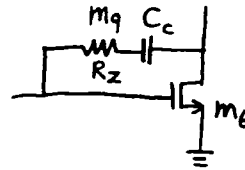
$$\frac{1}{r_{o7}} = \frac{20 \mu}{6.4 \mu} \cdot 0.1 \mu = 313 n$$

$$\frac{1}{r_{o6}} = \frac{20 \mu}{6.4 \mu} \cdot 0.2 \mu = 625 n$$

$$\frac{V_o}{V_i} = g_{m2} (r_{o2} \parallel r_{o4}) g_{m6} (r_{o6} \parallel r_{o7})$$

$$= 97.1 \mu (2.13 M) (194 \mu) (1.07 M)$$

$$= 4.28 \times 10^4 \text{ low frequency open loop gain}$$



$$Z = \frac{-1}{C_c (R_z - \frac{1}{g_{m6}})}$$

cancel this zero by moving it to
Infinity: $R_z = \frac{1}{g_{m6}} = 5.15 k$

$$\frac{1}{R_z} = \frac{\partial I_D}{\partial V_{DS}} = k (V_{GS} - V_t - V_{DS})$$

$$\approx k (V_G - V_S - V_t)$$

assume $r=0$

$$= k' \frac{W}{L} (5V - V_{GS6} - 0.7V)$$

$$\frac{1}{5.15 k} = 60.4 \mu \frac{W}{L} (5 - 0.906V - 0.7V)$$

$$= 205 \mu \frac{W}{L}$$

$$0.95 = \frac{W}{L_{eff}} = \frac{6.1 \mu}{6.4 \mu}$$

$$\left(\frac{W}{L}\right)_9 = \frac{6.1 \mu}{8 \mu}$$

$$V_{GS6} = \sqrt{\frac{2 I_D}{k_n' \frac{W}{L_{eff}}}} + V_t$$

$$= \sqrt{\frac{2 (20 \mu)}{60.4 \mu \frac{100 \mu}{6.4 \mu}}} + 0.7$$

$$= 0.906V$$

$$\frac{V_o}{V_i} = \frac{V_o}{i} \frac{i}{V_i} = \frac{1}{sC} g_{m2} = \frac{g_{m2}}{s}$$

$$\frac{V_o}{V_i}(j\omega) = \frac{g_m}{j\omega}$$

$$\text{unity gain } \omega = \frac{g_{m2}}{C} = \frac{97.1\mu}{5pF}$$

$$= 19.4 \text{ M rad/s}$$

$$3.09 \text{ MHz}$$

$$SR = \frac{dV_o}{dt} \max = \frac{I_{C \max}}{C} = \frac{20\mu A}{5pF}$$

$$= 4 \times 10^6 \frac{V}{s} = 4 \frac{V}{\mu s}$$

```

CMOS AMP
VDD 1 0 5V
VSS 2 0 -5V
M1 7 5 4 4 P W=100U L=6.4U
M2 8 6 4 4 P W=100U L=6.4U
M3 7 7 2 2 N W=50U L=6.4U
M4 8 7 2 2 N W=50U L=6.4U
M5 4 3 1 1 P W=100U L=6.4U
M7 9 3 1 1 P W=100U L=6.4U
M8 3 3 1 1 P W=100U L=6.4U
M6 9 8 2 2 N W=100U L=6.4U
IBIAS 3 2 20UA
M9 10 1 8 2 N W=6.1U L=6.4U
CCOMP 10 9 5PF

```

```

*NMOS: LAMBDA=(DSD/DVDS)/LEFF=0.2U/6.4U=0.0313
*PMOS: LAMBDA=(DSD/DVDS)/LEFF=0.1U/6.4U=0.0156
.MODEL N NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313
.MODEL P PMOS KP=30.2U VTO=-0.7 LAMBDA=0.0156
V11 5 0 -480V
V12 6 0 0V AC
.TF V(9) V11
.PLOT AC V(9)
.AC DEC 40 1000 10000
.OPTIONS NOPAGE NOMOD
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

```

+0:1 = 5.000E+00 0:2 = -5.000E+00 0:3 = 4.011E+00
+0:4 = 9.029E-01 0:5 = -4.800E-05 0:6 = 0.
+0:7 = -4.092E+00 0:8 = -4.102E+00 0:9 = -8.085E-03
+0:10 = -4.102E+00

```

**** MOSFETS

```

ELEMENT 0:M1 0:M2 0:M3 0:M4 0:M5 0:M7
MODEL 0:P 0:P 0:N 0:N 0:P 0:P
ID -1.048E-05 -1.048E-05 1.048E-05 1.048E-05 -2.096E-05 -2.123E-05
IBS 0. 0. 0. 0. 0. 0.
IBD 4.995E-14 5.006E-14 -9.078E-15 -8.973E-15 4.097E-14 5.008E-14
VGS -9.030E-01 -9.029E-01 9.078E-01 9.078E-01 -9.889E-01 -9.889E-01
VDS -4.995E+00 -5.005E+00 9.078E-01 8.973E-01 -4.097E+00 -5.008E+00
VBS 0. 0. 0. 0. 0. 0.
VTH -7.000E-01 -7.000E-01 7.000E-01 7.000E-01 -7.000E-01 -7.000E-01
VDSAT -2.030E-01 -2.029E-01 2.078E-01 2.078E-01 -2.889E-01 -2.889E-01
BETA 5.086E-04 5.087E-04 4.853E-04 4.851E-04 5.020E-04 5.087E-04
GAM KFF 0. 0. 0. 0. 0. 0.
GM 1.032E-04 1.032E-04 1.009E-04 1.008E-04 1.451E-04 1.470E-04
GDS 1.517E-07 1.516E-07 3.189E-07 3.189E-07 3.073E-07 3.073E-07
GMS 0. 0. 0. 0. 0. 0.
COTOT 0. 0. 0. 0. 0. 0.
CGTOT 0. 0. 0. 0. 0. 0.
CSTOT 0. 0. 0. 0. 0. 0.
CBTOT 0. 0. 0. 0. 0. 0.
CGS 0. 0. 0. 0. 0. 0.
CGD 0. 0. 0. 0. 0. 0.

```

```

ELEMENT 0:M8 0:M6 0:M9
MODEL 0:P 0:N 0:N
ID -2.000E-05 2.123E-05 -9.063E-13
IBS 0. 0. -8.973E-15
IBD 9.889E-15 -4.992E-14 -8.973E-15
VGS -9.889E-01 8.973E-01 9.102E+00

```

```

VDS -9.889E-01 4.991E+00 -1.873E-09
VBS 0. 0. -8.973E-01
VTH -7.000E-01 7.000E-01 7.000E-01
VDSAT -2.889E-01 1.973E-01 1.873E-09
BETA 4.792E-04 1.091E-03 5.757E-05
GAM KFF 0. 0. 0.
GM 1.384E-04 2.153E-04 1.079E-13
GDS 3.073E-07 5.748E-07 4.837E-04
GMS 0. 0. 0.
COTOT 0. 0. 0.
CGTOT 0. 0. 0.
CSTOT 0. 0. 0.
CBTOT 0. 0. 0.
CGS 0. 0. 0.
CGD 0. 0. 0.

```

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(9)/V11 = -5.345E+04
INPUT RESISTANCE AT V11 = 9.999E+19
OUTPUT RESISTANCE AT V(9) = 1.133E+06

```

***** AC ANALYSIS THOM= 27.000 TEMP= 27.000

```

FREQ V(9)
(A) 0. 1.000E+00 2.000E+00 3.000E+00 4.000E+00
1.000E+06 3.26E+00 + + + + + A + + +
1.059E+06 3.08E+00 + + + + + A + + +
1.122E+06 2.91E+00 + + + + + A + + +
1.188E+06 2.75E+00 + + + + + A + + +
1.258E+06 2.60E+00 + + + + + A + + +
1.333E+06 2.45E+00 + + + + + A + + +
1.412E+06 2.32E+00 + + + + + A + + +
1.496E+06 2.19E+00 + + + + + A + + +
1.584E+06 2.07E+00 + + + + + A + + +
1.678E+06 1.95E+00 + + + + + A + + +
1.778E+06 1.85E+00 + + + + + A + + +
1.883E+06 1.75E+00 + + + + + A + + +
1.995E+06 1.65E+00 + + + + + A + + +
2.113E+06 1.56E+00 + + + + + A + + +
2.238E+06 1.47E+00 + + + + + A + + +
2.371E+06 1.39E+00 + + + + + A + + +
2.511E+06 1.32E+00 + + + + + A + + +
2.660E+06 1.25E+00 + + + + + A + + +
2.818E+06 1.18E+00 + + + + + A + + +
2.985E+06 1.12E+00 + + + + + A + + +
3.162E+06 1.06E+00 + + + + + A + + +
3.349E+06 1.00E+00 + + + + + A + + +
3.548E+06 9.55E-01 + + + + + A + + +
3.758E+06 9.06E-01 + + + + + A + + +
3.981E+06 8.60E-01 + + + + + A + + +
4.217E+06 8.16E-01 + + + + + A + + +
4.466E+06 7.76E-01 + + + + + A + + +
4.731E+06 7.37E-01 + + + + + A + + +
5.011E+06 7.02E-01 + + + + + A + + +
5.308E+06 6.68E-01 + + + + + A + + +
5.623E+06 6.37E-01 + + + + + A + + +
5.956E+06 6.07E-01 + + + + + A + + +
6.309E+06 5.80E-01 + + + + + A + + +
6.683E+06 5.54E-01 + + + + + A + + +
7.079E+06 5.30E-01 + + + + + A + + +
7.498E+06 5.08E-01 + + + + + A + + +
7.943E+06 4.88E-01 + + + + + A + + +
8.414E+06 4.69E-01 + + + + + A + + +
8.912E+06 4.51E-01 + + + + + A + + +
9.440E+06 4.34E-01 + + + + + A + + +
1.000E+07 4.19E-01 + + + + + A + + +

```

```

CMOS AMP
VDD 1 0 5V
VSS 2 0 -5V
M1 7 9 4 4 P W=100U L=6.4U
M2 8 6 4 4 P W=100U L=6.4U
M3 7 7 2 2 N W=50U L=6.4U
M4 8 7 2 2 N W=50U L=6.4U
M5 4 3 1 1 P W=100U L=6.4U
M7 9 3 1 1 P W=100U L=6.4U
M8 3 3 1 1 P W=100U L=6.4U
M6 9 8 2 2 N W=100U L=6.4U
IBIAS 3 2 20UA
M9 10 1 8 2 N W=6.1U L=6.4U
CCOMP 10 9 5PF
*NMOS: LAMBDA=(DSD/DVDS)/LEFF=0.2U/6.4U=0.0313
*PMOS: LAMBDA=(DSD/DVDS)/LEFF=0.1U/6.4U=0.0156
.MODEL N NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313
.MODEL P PMOS KP=30.2U VTO=-0.7 LAMBDA=0.0156
V12 6 0 PULSE -2 2 0 0 30US
.PLOT TRAN V(9)
.TRAN 0.05U 1.8U
.OPTIONS NOPAGE NOMOD
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.WIDTH OUT=80
.OPTIONS SPICE
.END

```

***** TRANSIENT ANALYSIS

TMON= 27.000 TEMP= 27.000

TIME	V(9)					
(A)		-4.000E+00	-2.000E+00	0.	2.000E+00	4.000E+00
0.	-2.000E+00					
5.000E-08	-1.91E+00		A			
1.000E-07	-1.70E+00		A			
1.500E-07	-1.49E+00		A			
2.000E-07	-1.28E+00		A			
2.500E-07	-1.07E+00		A			
3.000E-07	-8.60E-01		A			
3.500E-07	-6.51E-01		A			
4.000E-07	-4.42E-01		A			
4.500E-07	-2.33E-01		A			
5.000E-07	-2.57E-02		A			
5.500E-07	1.81E-01		A			
6.000E-07	3.88E-01		A			
6.500E-07	5.94E-01		A			
7.000E-07	7.99E-01		A			
7.500E-07	1.00E+00		A			
8.000E-07	1.20E+00		A			
8.500E-07	1.41E+00		A			
9.000E-07	1.61E+00		A			
9.500E-07	1.84E+00		A			
1.000E-06	1.97E+00		A			
1.050E-06	1.99E+00		A			
1.100E-06	1.99E+00		A			
1.150E-06	2.00E+00		A			
1.200E-06	2.00E+00		A			
1.250E-06	2.00E+00		A			
1.300E-06	2.00E+00		A			
1.350E-06	2.00E+00		A			
1.400E-06	2.00E+00		A			
1.450E-06	2.00E+00		A			
1.500E-06	2.00E+00		A			
1.550E-06	2.00E+00		A			
1.600E-06	2.00E+00		A			
1.650E-06	2.00E+00		A			
1.700E-06	2.00E+00		A			
1.750E-06	2.00E+00		A			
1.800E-06	2.00E+00		A			

9.22

$$L_{eff} = L - 2L_d - X_d = 1 - 2 \times 0.09 - 0.1$$

$$= 0.72 \mu\text{m}$$

$|I_D| = 200 \mu\text{A}$ for M5-M8. $|I_D| = 100 \mu\text{A}$ for M1-M4.

From Table 2.4, $\frac{dX_d}{dV_{DS}} = 0.02 \mu\text{m/V}$ (NMOS)
 $0.04 \mu\text{m/V}$ (PMOS)

$$\frac{1}{r_o} = \frac{\partial I_D}{\partial V_{DS}} = \frac{I_D}{L_{eff}} \frac{dX_d}{dV_{DS}}$$

$$\frac{1}{r_{o2}} = \frac{100 \mu\text{A}}{0.72 \mu\text{m}} \cdot 0.04 \mu\text{m/V} = 5.55 \mu\text{A/V}$$

$$\frac{1}{r_{o4}} = \frac{100 \mu\text{A}}{0.72 \mu\text{m}} \cdot 0.02 \mu\text{m/V} = 2.78 \mu\text{A/V}$$

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{3.9 \times 8.854 \times 10^{-12}}{80 \times 10^{-10}} = 4.32 \times 10^{-3} \text{ F/m}^2$$

$$k'_p = \mu_p C_{ox} = 150 \times 10^{-4} \times 4.32 \times 10^{-3}$$

$$= 64.7 \mu\text{A/V}^2$$

$$k'_n = \mu_n C_{ox} = 450 \times 10^{-4} \times 4.32 \times 10^{-3}$$

$$= 194 \mu\text{A/V}^2$$

$$g_{m2} = \sqrt{2 \times 64.7 \times (150/0.72) \times 100} = 1.64 \text{ mA/V}$$

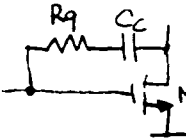
$$g_{m6} = \sqrt{2 \times 194 \times (100/0.72) \times 200} = 3.28 \text{ mA/V}$$

$$\frac{1}{r_{o7}} = \frac{200 \mu\text{A}}{0.72 \mu\text{m}} \cdot 0.04 \mu\text{m/V} = 11.1 \mu\text{A/V}$$

$$\frac{1}{r_{o6}} = \frac{200 \mu\text{A}}{0.72 \mu\text{m}} \cdot 0.02 \mu\text{m/V} = 5.55 \mu\text{A/V}$$

$$\frac{V_o}{V_i} = g_{m2}(r_{o4} \parallel r_{o4}) g_{m6}(r_{o6} \parallel r_{o7})$$

$$= \frac{1.64 \text{ m} \cdot 3.28 \text{ m}}{8.33 \mu \cdot 16.7 \mu} = 38700$$



$$Z = \frac{1}{(1/g_{m6} - R_q)C_c}$$

Cancel this zero by moving it to infinity.

$$R_q = 1/g_{m6} = 305 \Omega$$

$$\frac{1}{R_q} = \frac{\partial I_D}{\partial V_{DS}} = k' \left(\frac{W}{L} \right)_q (V_{GSq} - V_{Tq} - V_{DSq})$$

$$= k' \left(\frac{W}{L} \right)_q (V_{GSq} - V_{Ssq} - V_{Tq}) \quad (V_{DSq} = 0)$$

Assume $V = 0$

$$\frac{1}{R_q} = k' \left(\frac{W}{L} \right)_q (V_{GSq} - V_{SS} - V_{GS6} - V_{Tq})$$

$$= k' \left(\frac{W}{L} \right)_q (1.5 + 1.5 - V_{GS6} - V_{Tq})$$

$$V_{ov6} = \frac{2 \times 200}{\sqrt{194(100/0.72)}} = 0.122 \text{ V}$$

$$V_{GS6} = V_{T6} + V_{ov6} = 0.6 + 0.122 = 0.722 \text{ V}$$

$$\frac{1}{305} = 194 \times 10^{-6} \left(\frac{W}{L} \right)_q (3 - 0.722 - 0.6)$$

$$\left(\frac{W}{L} \right)_q = 10.0$$

M9 is in the triode region, so $X_d = 0$

Use the same drawn length as for M6.

$$L_q = 1 - 2 \times 0.09 = 0.82 \mu\text{m}$$

$$W_q = 8.2 \mu\text{m}$$

$$\text{At funity, } |A(\omega)| = \left| \frac{g_{m1}}{j\omega C_c} \right| = 1$$

$$f_{unity} = \frac{g_{m1}}{2\pi C_c} = \frac{1.64 \times 10^{-3}}{2\pi \times 5 \times 10^{-12}} = 52.2 \text{ MHz}$$

$$SR = \frac{I_{max}}{C_c} = \frac{200 \mu\text{A}}{5 \text{ pF}} = 40 \text{ V/}\mu\text{s}$$

9-16

```

CMOS AMP
VDD 1 0 1.5V
VSS 2 0 -1.5V
M1 7 5 4 4 P W=150U L=0.72U
M2 8 6 4 4 P W=150U L=0.72U
M3 7 7 2 2 N W=50U L=0.72U
M4 8 7 2 2 N W=50U L=0.72U
M5 4 3 1 1 P W=150U L=0.72U
M7 9 3 1 1 P W=150U L=0.72U
M8 3 3 1 1 P W=150U L=0.72U
M6 9 8 2 2 N W=100U L=0.72U
IBIAS 3 2 200UA
M9 10 1 8 2 N W=8.2U L=0.82U
CCOMP 10 9 5PF

```

```

* MODELS
.MODEL N NMOS LEVEL=1 KP=194U VTO=-0.6 LAMBDA=0.027778
.MODEL P PMOS LEVEL=1 KP=64.7U VTO=-0.8 LAMBDA=0.055556
*NMOS: LAMBDA=(DKD/DVDS)/LEFF=0.02U/0.72U=0.027778
*PMOS: LAMBDA=(DKD/DVDS)/LEFF=0.04U/0.72U=0.055556

```

```

V11 5 0 0 AC 1 PULSE 0 1 0 1NS 1NS 1US 30US
V12 6 0 0
.TF V(9) V11
.PLOT AC VDS(9)
.AC DEC 5 10 100MEG
.TRAN 0.005U 0.1U
.PLOT TRAN V(9)
.OPTIONS NOPAGE NOMOD
.OPTIONS VRTOL=1N ABSTOL=1F RELTOL=1U
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

```

***** OPERATING POINT INFORMATION      THSM= 27.000 TEMP= 27.000

+0:1      = 1.500E+00 0:2      = -1.500E+00 0:3      = 5.322E-01
+0:4      = 9.153E-01 0:5      = 0.      0:6      = 0.
+0:7      = -7.806E-01 0:8      = -7.806E-01 0:9      = 3.454E-01
+0:10     = -7.806E-01

```

**** MOSFETS

ELEMENT	0:M1	0:M2	0:M3	0:M4	0:M5	0:M7
MODEL	0:P	0:P	0:N	0:N	0:P	0:P
ID	-9.798E-05	-9.798E-05	9.798E-05	9.798E-05	-1.960E-04	-2.020E-04
IBS	0.	0.	0.	0.	0.	0.
IBD	1.696E-14	1.696E-14	-7.194E-15	-7.194E-15	5.847E-15	1.155E-14
VGS	-9.153E-01	-9.153E-01	7.194E-01	7.194E-01	-9.678E-01	-9.678E-01
VDS	-1.695E+00	-1.695E+00	7.194E-01	7.194E-01	-5.847E-01	-1.154E+00
VBS	0.	0.	0.	0.	0.	0.
VTH	-8.000E-01	-8.000E-01	6.000E-01	6.000E-01	-8.000E-01	-8.000E-01
VDSAT	-1.153E-01	-1.153E-01	1.194E-01	1.194E-01	-1.678E-01	-1.678E-01
BETA	1.475E-02	1.475E-02	1.374E-02	1.374E-02	1.392E-02	1.434E-02
GAM EFF	0.	0.	0.	0.	0.	0.
GM	1.700E-03	1.700E-03	1.641E-03	1.641E-03	2.335E-03	2.407E-03
GDS	4.975E-06	4.975E-06	2.668E-06	2.668E-06	1.054E-05	1.054E-05
GMB	0.	0.	0.	0.	0.	0.
CUTOT	0.	0.	0.	0.	0.	0.
CGTOT	0.	0.	0.	0.	0.	0.
CSTOT	0.	0.	0.	0.	0.	0.
CBTOT	0.	0.	0.	0.	0.	0.
CGS	0.	0.	0.	0.	0.	0.
CGD	0.	0.	0.	0.	0.	0.

ELEMENT	0:M8	0:M6	0:M9
MODEL	0:P	0:N	0:N
ID	-2.000E-04	2.020E-04	-7.266E-13
IBS	0.	0.	-7.194E-15
IBD	9.678E-15	-1.845E-14	-7.194E-15
VGS	-9.678E-01	7.194E-01	2.280E+00
VDS	-9.678E-01	1.845E+00	-2.229E-10
VBS	0.	0.	-7.194E-01
VTH	-8.000E-01	6.000E-01	6.000E-01
VDSAT	-1.678E-01	1.194E-01	2.229E-10
BETA	1.420E-02	2.833E-02	1.940E-03
GAM EFF	0.	0.	0.
GM	2.384E-03	3.383E-03	4.324E-13
GDS	1.054E-05	5.337E-06	3.260E-03
GMB	0.	0.	0.
CUTOT	0.	0.	0.
CGTOT	0.	0.	0.
CSTOT	0.	0.	0.
CBTOT	0.	0.	0.
CGS	0.	0.	0.
CGD	0.	0.	0.

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(9)/V11      = -4.733E+04
INPUT RESISTANCE AT V11      = 9.999E+19
OUTPUT RESISTANCE AT V(9)    = 6.296E+04

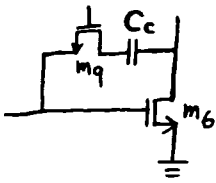
```

***** AC ANALYSIS THSM= 27.000 TEMP= 27.000

FREQ	VDS(9)	0.	5.000E+01	1.000E+02	1.500E+02
(A)	-5.000E+01	0.	5.000E+01	1.000E+02	1.500E+02
1.000E+01	9.35E+01	0.	0.	0.	0.
1.584E+01	9.35E+01	0.	0.	0.	0.
2.511E+01	9.35E+01	0.	0.	0.	0.
3.981E+01	9.35E+01	0.	0.	0.	0.
6.309E+01	9.34E+01	0.	0.	0.	0.
1.000E+02	9.34E+01	0.	0.	0.	0.
1.584E+02	9.34E+01	0.	0.	0.	0.
2.511E+02	9.33E+01	0.	0.	0.	0.
3.981E+02	9.30E+01	0.	0.	0.	0.
6.309E+02	9.23E+01	0.	0.	0.	0.
1.000E+03	9.10E+01	0.	0.	0.	0.
1.584E+03	8.87E+01	0.	0.	0.	0.
2.511E+03	8.57E+01	0.	0.	0.	0.
3.981E+03	8.22E+01	0.	0.	0.	0.
6.309E+03	7.84E+01	0.	0.	0.	0.
1.000E+04	7.45E+01	0.	0.	0.	0.
1.584E+04	7.05E+01	0.	0.	0.	0.
2.511E+04	6.65E+01	0.	0.	0.	0.
3.981E+04	6.25E+01	0.	0.	0.	0.
6.309E+04	5.85E+01	0.	0.	0.	0.
1.000E+05	5.45E+01	0.	0.	0.	0.
1.584E+05	5.05E+01	0.	0.	0.	0.
2.511E+05	4.65E+01	0.	0.	0.	0.
3.981E+05	4.25E+01	0.	0.	0.	0.
6.309E+05	3.85E+01	0.	0.	0.	0.
1.000E+06	3.45E+01	0.	0.	0.	0.
1.584E+06	3.05E+01	0.	0.	0.	0.
2.511E+06	2.65E+01	0.	0.	0.	0.
3.981E+06	2.25E+01	0.	0.	0.	0.
6.309E+06	1.85E+01	0.	0.	0.	0.
1.000E+07	1.45E+01	0.	0.	0.	0.
1.584E+07	1.05E+01	0.	0.	0.	0.
2.511E+07	6.58E+00	0.	0.	0.	0.
3.981E+07	2.58E+00	0.	0.	0.	0.
6.309E+07	-1.41E+00	0.	0.	0.	0.
1.000E+08	-5.40E+00	0.	0.	0.	0.

***** TRANSIENT ANALYSIS THSM= 27.000 TEMP= 27.000

TIME	V(9)	-1.500E+00	-1.000E-00	-5.000E-01	0.	5.000E-01
(A)	-1.500E+00	-1.000E-00	-5.000E-01	0.	5.000E-01	
0.	3.45E-01	0.	0.	0.	0.	
5.000E-09	1.39E-01	0.	0.	0.	0.	
1.000E-08	-5.57E-02	0.	0.	0.	0.	
1.500E-08	-2.50E-01	0.	0.	0.	0.	
2.000E-08	-4.45E-01	0.	0.	0.	0.	
2.500E-08	-6.40E-01	0.	0.	0.	0.	
3.000E-08	-8.34E-01	0.	0.	0.	0.	
3.500E-08	-1.02E+00	0.	0.	0.	0.	
4.000E-08	-1.22E+00	0.	0.	0.	0.	
4.500E-08	-1.39E+00	0.	0.	0.	0.	
5.000E-08	-1.45E+00	0.	0.	0.	0.	
5.500E-08	-1.47E+00	0.	0.	0.	0.	
6.000E-08	-1.47E+00	0.	0.	0.	0.	
6.500E-08	-1.48E+00	0.	0.	0.	0.	
7.000E-08	-1.48E+00	0.	0.	0.	0.	
7.500E-08	-1.48E+00	0.	0.	0.	0.	
8.000E-08	-1.49E+00	0.	0.	0.	0.	
8.500E-08	-1.49E+00	0.	0.	0.	0.	
9.000E-08	-1.49E+00	0.	0.	0.	0.	
9.500E-08	-1.49E+00	0.	0.	0.	0.	
1.000E-07	-1.49E+00	0.	0.	0.	0.	

9.23

$$\text{zero } z = \frac{-1}{C_c(R_z - \frac{1}{g_{m6}})}$$

$$\text{set } R_z = \frac{1}{g_{m6}} = \frac{1}{194 \mu} = 5.15 \text{ k}$$

$$g_{m6} = \sqrt{2 k n' \frac{W}{L_{\text{eff}}} I_D}$$

$$= \sqrt{2 (60.4 \mu) \frac{100}{6.4} 20 \mu}$$

$$= 194 \mu$$

$$\frac{1}{R_z} = \frac{\partial I_D}{\partial V_{DS}} = k (V_{GS} - V_t - V_{DS})$$

$$= k (V_{GSq} - V_t) \big|_{V_{DS}=0}$$

$$= g_{m9}$$

$$R_z = \frac{1}{g_{m9}} = \frac{1}{g_{m6}}$$

$$\text{set } k_9 (V_{GSq} - V_t) = k_6 (V_{GS6} - V_t)$$

$$k_n \left(\frac{W}{L} \right)_9 (V_{GSq} - V_t) = k_n \left(\frac{W}{L} \right)_6 (V_{GS6} - V_t)$$

assume $\gamma=0$, $V_t = 0.7 \text{ V}$ for
all devices

KVL

$$V_{GS12} + V_{GS11} = V_{GS9} + V_{GS6}$$

$$V_{GS12} = V_{GS11} = V_{GS6}$$

$$\therefore V_{GS6} = V_{GS9}$$

$$\left(\frac{W}{L} \right)_9 (V_{GSq} - V_t) = \left(\frac{W}{L} \right)_6 (V_{GS6} - V_t)$$

$$\left(\frac{W}{L} \right)_9 = \left(\frac{W}{L} \right)_6$$

9-18

CMOS AMP WITHOUT M9, SEE RIGHT HALF PLANE ZERO

```
VDD 1 0 5V
VSS 2 0 -5V
M1 7 5 4 4 P W=100U L=6.4U
M2 8 6 4 4 P W=100U L=6.4U
M3 7 7 2 2 N W=50U L=6.4U
M4 8 7 2 2 N W=50U L=6.4U
M5 4 3 1 1 P W=100U L=6.4U
M7 9 3 1 1 P W=100U L=6.4U
M8 3 3 1 1 P W=100U L=6.4U
M6 9 8 2 2 N W=100U L=6.4U
IBIAS 3 2 20UA
CCOMP 8 9 5PF
```

```
*NMOS: LAMBDA=(DXD/DVDS)/LEFF=0.2U/6.4U=0.0313
*PMOS: LAMBDA=(DXD/DVDS)/LEFF=0.1U/6.4U=0.0156
.MODEL N NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313
.MODEL P PMOS KP=30.2U VTO=-0.7 LAMBDA=0.0156
```

V11 5 0 -48UV

V12 6 0 0V AC

.TF V(9) V11

.PLOT AC VP(9)

.AC DEC 10 100K 10GIG

.OPTIONS NOPAGE NOMOD

.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U

.WIDTH OUT=80

.OPTIONS SPICE

.OP

.END

***** AC ANALYSIS THOM= 27.000 TEMP= 27.000

FREQ	VP(9)
(A)	-2.000E+02 -1.500E+02 -1.000E+02 -5.000E+01 0.

1.000E+05	-9.08E+01	+	+	+	+	+	+	+	+
1.258E+05	-9.10E+01	+	+	+	+	+	+	+	+
1.584E+05	-9.13E+01	+	+	+	+	+	+	+	+
1.995E+05	-9.16E+01	+	+	+	+	+	+	+	+
2.511E+05	-9.20E+01	+	+	+	+	+	+	+	+
3.162E+05	-9.26E+01	+	+	+	+	+	+	+	+
3.981E+05	-9.33E+01	+	+	+	+	+	+	+	+
5.011E+05	-9.41E+01	+	+	+	+	+	+	+	+
6.309E+05	-9.52E+01	+	+	+	+	+	+	+	+
7.943E+05	-9.66E+01	+	+	+	+	+	+	+	+
1.000E+06	-9.83E+01	+	+	+	+	+	+	+	+
1.258E+06	-1.00E+02	+	+	+	+	+	+	+	+
1.584E+06	-1.03E+02	+	+	+	+	+	+	+	+
1.995E+06	-1.06E+02	+	+	+	+	+	+	+	+
2.511E+06	-1.10E+02	+	+	+	+	+	+	+	+
3.162E+06	-1.14E+02	+	+	+	+	+	+	+	+
3.981E+06	-1.20E+02	+	+	+	+	+	+	+	+
5.011E+06	-1.26E+02	+	+	+	+	+	+	+	+
6.309E+06	-1.32E+02	+	+	+	+	+	+	+	+
7.943E+06	-1.39E+02	+	+	+	+	+	+	+	+
1.000E+07	-1.45E+02	+	+	+	+	+	+	+	+
1.258E+07	-1.51E+02	+	+	+	+	+	+	+	+
1.584E+07	-1.56E+02	+	+	+	+	+	+	+	+
1.995E+07	-1.61E+02	+	+	+	+	+	+	+	+
2.511E+07	-1.64E+02	+	+	+	+	+	+	+	+
3.162E+07	-1.67E+02	+	+	+	+	+	+	+	+
3.981E+07	-1.70E+02	+	+	+	+	+	+	+	+
5.011E+07	-1.72E+02	+	+	+	+	+	+	+	+
6.309E+07	-1.73E+02	+	+	+	+	+	+	+	+
7.943E+07	-1.75E+02	+	+	+	+	+	+	+	+
1.000E+08	-1.76E+02	+	+	+	+	+	+	+	+
1.258E+08	-1.76E+02	+	+	+	+	+	+	+	+
1.584E+08	-1.77E+02	+	+	+	+	+	+	+	+
1.995E+08	-1.78E+02	+	+	+	+	+	+	+	+
2.511E+08	-1.78E+02	+	+	+	+	+	+	+	+
3.162E+08	-1.78E+02	+	+	+	+	+	+	+	+
3.981E+08	-1.79E+02	+	+	+	+	+	+	+	+
5.011E+08	-1.79E+02	+	+	+	+	+	+	+	+
6.309E+08	-1.79E+02	+	+	+	+	+	+	+	+
7.943E+08	-1.79E+02	+	+	+	+	+	+	+	+
1.000E+09	-1.79E+02	+	+	+	+	+	+	+	+

CMOS AMP WITH M9 TO MOVE RIGHT HALF PLANE ZERO TO INFINITY

VDD 1 0 5V

VSS 2 0 -5V

M1 7 5 4 4 P W=100U L=6.4U

M2 8 6 4 4 P W=100U L=6.4U

M3 7 7 2 2 N W=50U L=6.4U

M4 8 7 2 2 N W=50U L=6.4U

M5 4 3 1 1 P W=100U L=6.4U

M7 9 3 1 1 P W=100U L=6.4U

M8 3 3 1 1 P W=100U L=6.4U

M6 9 8 2 2 N W=100U L=6.4U

IBIAS 3 2 20UA

M9 10 12 8 2 N W=100U L=6.4U

CCOMP 10 9 5PF

*BIAS CIRCUITRY FOR M9

M10 12 3 1 1 P W=100U L=6.4U

M11 12 12 13 2 N W=100U L=6.4U

M12 13 13 2 2 N W=100U L=6.4U

*NMOS: LAMBDA=(DXD/DVDS)/LEFF=0.2U/6.4U=0.0313

*PMOS: LAMBDA=(DXD/DVDS)/LEFF=0.1U/6.4U=0.0156

.MODEL N NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313

.MODEL P PMOS KP=30.2U VTO=-0.7 LAMBDA=0.0156

V11 5 0 -48UV

V12 6 0 0V AC

.TF V(9) V11

.PLOT AC VP(9)

.AC DEC 10 100K 10GIG

.OPTIONS NOPAGE NOMOD

.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U

.WIDTH OUT=80

.OPTIONS SPICE

.OP

.END

***** AC ANALYSIS THOM= 27.000 TEMP= 27.000

FREQ	VP(9)
(A)	-1.600E+02 -1.400E+02 -1.200E+02 -1.000E+02 -8.000E+01

1.000E+05	-8.99E+01	+	+	+	+	+	+	+	+
1.258E+05	-8.99E+01	+	+	+	+	+	+	+	+
1.584E+05	-8.99E+01	+	+	+	+	+	+	+	+
1.995E+05	-9.00E+01	+	+	+	+	+	+	+	+
2.511E+05	-9.00E+01	+	+	+	+	+	+	+	+
3.162E+05	-9.00E+01	+	+	+	+	+	+	+	+
3.981E+05	-9.00E+01	+	+	+	+	+	+	+	+
5.011E+05	-9.00E+01	+	+	+	+	+	+	+	+
6.309E+05	-9.00E+01	+	+	+	+	+	+	+	+
7.943E+05	-9.00E+01	+	+	+	+	+	+	+	+
1.000E+06	-9.00E+01	+	+	+	+	+	+	+	+
1.258E+06	-9.01E+01	+	+	+	+	+	+	+	+
1.584E+06	-9.01E+01	+	+	+	+	+	+	+	+
1.995E+06	-9.01E+01	+	+	+	+	+	+	+	+
2.511E+06	-9.02E+01	+	+	+	+	+	+	+	+
3.162E+06	-9.02E+01	+	+	+	+	+	+	+	+
3.981E+06	-9.03E+01	+	+	+	+	+	+	+	+
5.011E+06	-9.04E+01	+	+	+	+	+	+	+	+
6.309E+06	-9.05E+01	+	+	+	+	+	+	+	+
7.943E+06	-9.06E+01	+	+	+	+	+	+	+	+
1.000E+07	-9.08E+01	+	+	+	+	+	+	+	+
1.258E+07	-9.11E+01	+	+	+	+	+	+	+	+
1.584E+07	-9.13E+01	+	+	+	+	+	+	+	+
1.995E+07	-9.17E+01	+	+	+	+	+	+	+	+
2.511E+07	-9.21E+01	+	+	+	+	+	+	+	+
3.162E+07	-9.27E+01	+	+	+	+	+	+	+	+
3.981E+07	-9.34E+01	+	+	+	+	+	+	+	+
5.011E+07	-9.43E+01	+	+	+	+	+	+	+	+
6.309E+07	-9.55E+01	+	+	+	+	+	+	+	+
7.943E+07	-9.69E+01	+	+	+	+	+	+	+	+
1.000E+08	-9.86E+01	+	+	+	+	+	+	+	+
1.258E+08	-1.00E+02	+	+	+	+	+	+	+	+
1.584E+08	-1.03E+02	+	+	+	+	+	+	+	+
1.995E+08	-1.06E+02	+	+	+	+	+	+	+	+
2.511E+08	-1.11E+02	+	+	+	+	+	+	+	+
3.162E+08	-1.15E+02	+	+	+	+	+	+	+	+
3.981E+08	-1.21E+02	+	+	+	+	+	+	+	+
5.011E+08	-1.27E+02	+	+	+	+	+	+	+	+
6.309E+08	-1.33E+02	+	+	+	+	+	+	+	+
7.943E+08	-1.40E+02	+	+	+	+	+	+	+	+
1.000E+09	-1.46E+02	+	+	+	+	+	+	+	+

THE POLE AT 6.3 MHZ HAS BEEN MOVED UP IN FREQUENCY.

V12 6 0 0V AC

.TF V(9) V11

.PLOT AC VP(9)

.AC DEC 10 100K 1GIG

.OPTIONS NOPAGE NOMOD

.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U

.WIDTH OUT=80

.OPTIONS SPICE

.OP

.END

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

+0:1 = 5.000E+00 0:2 =-5.000E+00 0:3 = 4.011E+00

+0:4 = 9.029E-01 0:5 =-4.800E-05 0:6 = 0.

+0:7 =-4.092E+00 0:8 =-4.102E+00 0:9 =-8.085E-03

+0:10 =-4.102E+00 0:12 =-3.172E+00 0:13 =-4.086E+00

**** MOSFETS

ELEMENT 0:M1 0:M2 0:M3 0:M4 0:M5 0:M7

MODEL 0:P 0:P 0:N 0:N 0:P 0:P

ID -1.048E-05 -1.048E-05 1.048E-05 1.048E-05 -2.096E-05 -2.123E-05

IBS 0. 0. 0. 0. 0. 0.

IBD 4.995E-14 5.006E-14 -9.078E-15 -8.973E-15 4.097E-14 5.008E-14

VGS -9.030E-01 -9.029E-01 9.078E-01 9.078E-01 -9.889E-01 -9.889E-01

VDS -4.995E+00 -5.005E+00 9.078E-01 8.973E-01 -4.097E+00 -5.008E+00

VBS 0. 0. 0. 0. 0. 0.

VTH -7.000E-01 -7.000E-01 7.000E-01 7.000E-01 -7.000E-01 -7.000E-01

VDSAT -2.030E-01 -2.029E-01 2.078E-01 2.078E-01 -2.889E-01 -2.889E-01

BETA 5.086E-04 5.087E-04 4.853E-04 4.851E-04 5.020E-04 5.087E-04

GAM EFF 0. 0. 0. 0. 0. 0.

GM 1.032E-04 1.032E-04 1.009E-04 1.008E-04 1.451E-04 1.470E-04

GDS 1.517E-07 1.516E-07 3.189E-07 3.189E-07 3.073E-07 3.073E-07

GMB 0. 0. 0. 0. 0. 0.

ELEMENT 0:M8 0:M6 0:M9 0:M10 0:M11 0:M12

MODEL 0:P 0:N 0:N 0:P 0:N 0:N

ID -2.000E-05 2.123E-05 -9.063E-13 -2.221E-05 2.221E-05 2.221E-05

IBS 0. 0. -8.973E-15 0. -9.139E-15 0.

IBD 9.889E-15 -4.992E-14 -8.973E-15 8.172E-14 -1.828E-14 -9.139E-15

VGS -9.889E-01 8.973E-01 9.305E-01 -9.889E-01 9.139E-01 9.139E-01

VDS -9.889E-01 4.991E+00 -4.166E-09 -8.172E+00 9.139E-01 9.139E-01

VBS 0. 0. -8.973E-01 0. -9.139E-01 0.

VTH -7.000E-01 7.000E-01 7.000E-01 -7.000E-01 7.000E-01 7.000E-01

VDSAT -2.889E-01 1.973E-01 4.166E-09 -2.889E-01 2.139E-01 2.139E-01

BETA 4.792E-04 1.091E-03 9.438E-04 5.320E-04 9.707E-04 9.707E-04

GAM EFF 0. 0. 0. 0. 0. 0.

GM 1.384E-04 2.153E-04 3.931E-12 1.537E-04 2.076E-04 2.076E-04

GDS 3.073E-07 5.748E-07 2.175E-04 3.073E-07 6.758E-07 6.758E-07

GMB 0. 0. 0. 0. 0. 0.

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(9)/V11 = -5.345E+04

INPUT RESISTANCE AT V11 = 9.999E+19

OUTPUT RESISTANCE AT V(9) = 1.133E+06

***** AC ANALYSIS THOM= 27.000 TEMP= 27.000

FREQ	VP(9)
(A)	-1.600E+02 -1.400E+02 -1.200E+02 -1.000E+02 -8.000E+01

9-19

9.24

From Problem 9.22,

$$\frac{1}{R_9} = k' \left(\frac{W}{L} \right)_9 (V_{GS9} - V_{t9})$$

Since $I_{D12} = I_{D6}$ and $(W/L)_{12} = (W/L)_6$,

$$V_{OV12} = V_{OV6}$$

Therefore $V_{SB11} = V_{GS12} = V_{t12} + V_{OV12}$

$$= V_{SB9} = V_{GS6} = V_{t6} + V_{OV6},$$

because $V_{t12} = V_{t6}$ (no body effect).Also, $V_{OV11} = V_{OV2}$ because $I_{D11} = I_{D12}$ and

$$(W/L)_{11} = (W/L)_{12}$$

Therefore, $V_{GS9} = V_{GS11} + V_{GS12} - V_{GS6}$

$$= V_{t11} + V_{OV11} + V_{t12} + V_{OV12} - V_{t6} - V_{OV6}$$

$$= V_{t11} + V_{OV},$$

where $V_{OV} = V_{OV6} = V_{OV11} = V_{OV12}$.So $V_{GS9} - V_{t9} = V_{t11} + V_{OV} - V_{t9} = V_{OV}$.Since $V_{GS9} - V_{t9} = V_{GS6} - V_{t6}$ and $\frac{1}{R_9}$ should equal g_{m6} to cancel the RHP zero,

$$\frac{1}{R_9} = k' \left(\frac{W}{L} \right)_9 (V_{GS9} - V_{t9})$$

$$= g_{m6} = k' \left(\frac{W}{L} \right)_6 (V_{GS6} - V_{t6})$$

$$\left(\frac{W}{L} \right)_9 = \left(\frac{W}{L} \right)_6 = \frac{100}{1}$$

9.25To get 45° phase margin,

set the 2nd pole = unity gain freq.

$$(|P_2| = \frac{g_{m6} C_c}{C_L C_1 + C_c C_L + C_1 C_c}) = \frac{g_{m2}}{C_c}$$

$$g_{m2} = 97.1 \mu A/V$$

$$g_{m6} = 194 \mu A/V$$

$$C_c = 5 \text{ pF}$$

$$C_1 = C_{OL2} + C_{OL4} + C_{gs6} + C_{OL9}$$

$$= 0.35 \frac{\text{fF}}{\mu} (100\mu + 50\mu)$$

$$+ \frac{2}{3} (100\mu)(8\mu) 0.869 \frac{\text{fF}}{\mu^2}$$

$$+ 0.35 \frac{\text{fF}}{\mu} (100\mu)$$

$$= 551 \text{ fF}$$

$$\frac{g_{m2}}{C_c} = 19.4 \text{ M rad/s}$$

$$19.4 \text{ M} = \frac{194 \mu (5 \text{ p})}{C_L 551 \text{ f} + C_L 5 \text{ p} + 551 \text{ f} (5 \text{ p})}$$

solve for C_L

$$C_L = 8.51 \text{ pF}$$

9.26

To obtain 45° phase margin, set the 2nd pole to funity

$$|P_2| = \frac{g_{m6}C_c}{C_L C_1 + C_c C_L + C_1 C_c} = \frac{g_{m2}}{C_c} = \frac{1.64 \text{ mA/V}}{5 \text{ pF}}$$

$$= 328 \text{ M rad/s}$$

C_1 is dominated by the gate of M6

Minimum estimate for $C_1 = C_{gs6(i)} + C_{gs6(o)}$

$$= \frac{2}{3} 100 \times 0.72 \times 4.3 + 0.35 \times 100 = 244 \text{ fF}$$

Maximum estimate for C_1

$$= C_{gs6(i)} + C_{gs6(o)} + C_{gs9(i)} + C_{gs9(o)} + C_{gd2(o)} + C_{gd4(o)}$$

$$= \frac{2}{3} 100 \times 0.72 \times 0.43 + 0.35 \times 100 + \frac{1}{2} 100 \times 0.82 + 0.35 \times 100 + 0.35 \times 150 + 0.35 \times 50$$

$$= 387 \text{ fF}$$

(M9 is in the triode region.)

$$328 \text{ M rad/s} = \frac{3.28 \text{ m(5p)}}{C_L C_1 + C_L(5p) + C_1(5p)}$$

Case 1 (min C_1)

$$C_L(244 \text{ fF}) + C_L(5p) + 244 \text{ f(5p)} = 5 \times 10^{-23}$$

$$C_L = 9.3 \text{ pF}$$

Case 2 (max C_1)

$$C_L(387 \text{ fF}) + C_L(5p) + 387 \text{ f(5p)} = 5 \times 10^{-23}$$

$$C_L = 8.9 \text{ pF}$$

Therefore, C_L should be less than about 8.9 pF

9.27

calculate capacitances
for SPICE input

$$W = 100\mu$$

nmos

$$C_{jsw} = 0.5 \frac{fF}{\mu} (204\mu) \\ = 102 fF$$

$$C_j = 0.08 \frac{fF}{\mu^2} 200\mu^2 \\ = 16 fF$$

$$C_{db} = C_{sb} = 102 + 16 \\ = 118 fF$$

$$W = 100\mu$$

pmos

$$C_{jsw} = 1.5 \frac{fF}{\mu} 204\mu \\ = 306 fF$$

$$C_j = 0.2 \frac{fF}{\mu^2} 200\mu^2 \\ = 40 fF$$

$$C_{db} = C_{sb} = 346 fF$$

$$W = 50\mu$$

nmos

$$C_{jsw} = 0.5 \frac{fF}{\mu} 104\mu \\ = 52 fF$$

$$C_j = 0.08 \frac{fF}{\mu^2} 100\mu^2 \\ = 8 fF$$

$$C_{db} = C_{sb} = 60 fF$$

from SPICE output of
forward path gain $a(j\omega)$

$$\omega_1 = 1.26 \text{ MHz}$$

$$\angle a(j\omega_1) = -100^\circ$$

$$\text{set } f_0 = \frac{1}{|a(j\omega_1)|} = \frac{1}{312} = 3.21 \text{ m}$$

$$\therefore |T(j\omega_1)| = |a(j\omega_1)| f_0 = 1$$

9-21

$$\therefore \text{phase margin} = 80^\circ$$

$$f_0 = \frac{R_x}{R_x + 1M}, R_x = 3.22 \text{ k}$$

$$\omega_2 = 3.98 \text{ MHz}$$

$$\angle a(j\omega_2) = -120^\circ$$

$$\text{set } f_0 = \frac{1}{|a(j\omega_2)|} = \frac{1}{90.1} = 11.1 \text{ m}$$

$$\therefore |T(j\omega_2)| = |a(j\omega_2)| f_0 = 1$$

$$\therefore \text{phase margin} = 60^\circ$$

$$f_0 = \frac{R_x}{R_x + 1M}, R_x = 11.2 \text{ k}$$

$$\omega_3 = 6.31 \text{ MHz}$$

$$\angle a(j\omega_3) = -135^\circ$$

$$\text{set } f_0 = \frac{1}{|a(j\omega_3)|} = \frac{1}{49.7} = 20.1 \text{ m}$$

$$\therefore |T(j\omega_3)| = |a(j\omega_3)| f_0 = 1$$

$$\therefore \text{phase margin} = 45^\circ$$

$$f_0 = \frac{R_x}{R_x + 1M}, R_x = 20.5 \text{ k}$$

$$\omega_4 = 12.6 \text{ MHz}$$

$$\angle a(j\omega_4) = -160^\circ$$

$$\text{set } f_0 = \frac{1}{|a(j\omega_4)|} = \frac{1}{16.1} = 62.2 \text{ m}$$

$$\therefore |T(j\omega_4)| = |a(j\omega_4)| f_0 = 1$$

$$\therefore \text{phase margin} = 20^\circ$$

$$f_0 = \frac{R_x}{R_x + 1M}, R_x = 66.3 \text{ k}$$

9-22

CMOS AMP, FORWARD PATH GAIN = A(JW)

VDD 1 0 5V

VSS 2 0 -5V

* ASSUME XD=1U. LEFF=L-XD-2LD=8U-1U-0.6U=6.4U

* ASSUME DRAIN/SOURCE REGIONS ARE 2U WIDE.

M1 7 5 4 4 P W=100U L=6.4U

M2 8 6 4 4 P W=100U L=6.4U

M3 7 7 2 2 N 50U W=50U L=6.4U

M4 8 7 2 2 N 50U W=50U L=6.4U

M5 4 3 1 1 P W=100U L=6.4U

M7 9 3 1 1 P W=100U L=6.4U

M8 3 3 1 1 P W=100U L=6.4U

M6 9 8 2 2 N 100U W=100U L=6.4U

IBIAS 3 2 20UA

RL 9 0 1MEG

*NMOS: LAMBDA=(DXD/DVDS)/LEFF=0.2U/6.4U=0.0313

*PMOS: LAMBDA=(DXD/DVDS)/LEFF=0.1U/6.4U=0.0156

.MODEL N_50U NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313 TOX=400E-10

+ CGSO=350PF CGDO=350PF CRD=60FF CBS=60FF

.MODEL N_100U NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313 TOX=400E-10

+ CGSO=350PF CGDO=350PF CRD=118FF CBS=118FF

.MODEL P_PMOS KP=30.2U VTO=-0.7 LAMBDA=0.0156 TOX=400E-10

+ CGSO=350PF CGDO=350PF CRD=346FF CBS=346FF

V1 5 0 -48UV

V12 6 0 0V AC

.TF V(9) V12

.PLOT AC V(9)

.PLOT AC VP(9)

.AC DEC 10 1K 20MEG

.OPTIONS NOPAGE NOMOD

.OPTIONS VMTOL=1N ABSTOL=1F RELTOL=1U

.WIDTH OUT=80

.OPTIONS SPICE

.OP

.END

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

+0:1 = 5.000E+00 0:2 = -5.000E+00 0:3 = 4.011E+00

+0:4 = 9.029E-01 0:5 = -4.800E-05 0:6 = 0.

+0:7 = -4.092E+00 0:8 = -4.102E+00 0:9 = -4.230E-03

**** MOSFETS

ELEMENT	0:M1	0:M2	0:M3	0:M4	0:M5	0:M7
MODEL	0:P	0:P	0:N_50U	0:N_50U	0:P	0:P
ID	-1.048E-05	-1.048E-05	1.048E-05	1.048E-05	-2.096E-05	-2.123E-05
IBS	0.	0.	0.	0.	0.	0.
IRD	4.995E-14	5.006E-14	-9.078E-15	-8.973E-15	4.097E-14	5.004E-14
VGS	-9.030E-01	-9.029E-01	9.078E-01	9.078E-01	-9.889E-01	-9.889E-01
VDS	-4.995E+00	-5.005E+00	9.078E-01	9.073E-01	-4.097E+00	-5.004E+00
VBS	0.	0.	0.	0.	0.	0.
VTH	-7.000E-01	-7.000E-01	7.000E-01	7.000E-01	-7.000E-01	-7.000E-01
VDSAT	-2.030E-01	-2.029E-01	2.078E-01	2.078E-01	-2.889E-01	-2.889E-01
BETA	5.086E-04	5.087E-04	4.853E-04	4.851E-04	5.020E-04	5.087E-04
GAM EFF	0.	0.	0.	0.	0.	0.
GM	1.032E-04	1.032E-04	1.009E-04	1.008E-04	1.451E-04	1.470E-04
GDS	1.517E-07	1.516E-07	3.189E-07	3.189E-07	3.073E-07	3.073E-07
GMB	0.	0.	0.	0.	0.	0.
CDTOT	1.672E-13	1.671E-13	5.890E-14	5.902E-14	1.779E-13	1.671E-13
CGTOT	4.872E-13	4.872E-13	2.416E-13	2.416E-13	4.729E-13	4.735E-13
CSTOT	7.493E-13	7.493E-13	2.617E-13	2.617E-13	7.493E-13	7.493E-13
CBTOT	5.197E-13	5.196E-13	1.231E-13	1.233E-13	5.174E-13	5.060E-13
CGS	4.033E-13	4.033E-13	2.017E-13	2.017E-13	4.033E-13	4.033E-13
CGD	3.868E-14	3.869E-14	1.783E-14	1.783E-14	3.802E-14	3.869E-14

ELEMENT	0:M8	0:M6
MODEL	0:P	0:N_100U
ID	-2.000E-05	2.124E-05
IBS	0.	0.
IRD	9.889E-15	-4.996E-14
VGS	-9.889E-01	8.973E-01
VDS	-9.889E-01	4.995E+00
VBS	0.	0.
VTH	-7.000E-01	7.000E-01
VDSAT	-2.889E-01	1.973E-01
BETA	4.792E-04	1.091E-03
GAM EFF	0.	0.
GM	1.384E-04	2.153E-04
GDS	3.073E-07	5.749E-07
GMB	0.	0.
CDTOT	2.671E-13	8.252E-14
CGTOT	4.706E-13	4.885E-13
CSTOT	7.493E-13	5.213E-13
CBTOT	6.089E-13	2.083E-13
CGS	4.033E-13	4.033E-13
CGD	3.573E-14	3.868E-14

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(9)/V12	= 2.505E+04
INPUT RESISTANCE AT V12	= 9.999E+19
OUTPUT RESISTANCE AT V(9)	= 5.313E+05

***** AC ANALYSIS THOM= 27.000 TEMP= 27.000

FREQ	7(9)	1.000E+04	2.000E+04	3.000E+04	4.000E+04
(A)	0.				
9.999E+02	2.508E+04				
1.258E+03	2.498E+04				
1.584E+03	2.498E+04				
1.995E+03	2.488E+04				
2.511E+03	2.468E+04				
3.162E+03	2.448E+04				
3.981E+03	2.412E+04				
5.011E+03	2.368E+04				
6.309E+03	2.298E+04				
7.943E+03	2.198E+04				
9.999E+03	2.058E+04				
1.258E+04	1.888E+04				
1.584E+04	1.688E+04				
1.995E+04	1.468E+04				
2.511E+04	1.248E+04				
3.162E+04	1.038E+04				
3.981E+04	8.508E+03				
5.011E+04	6.908E+03				
6.309E+04	5.568E+03				
7.943E+04	4.458E+03				
1.000E+05	3.568E+03				
1.258E+05	2.848E+03				
1.584E+05	2.268E+03				
1.995E+05	1.798E+03				
2.511E+05	1.438E+03				
3.162E+05	1.138E+03				
3.981E+05	9.028E+02				
5.011E+05	7.168E+02				
6.309E+05	5.688E+02				
7.943E+05	4.518E+02				
1.000E+06	3.578E+02				
1.258E+06	2.828E+02				
1.584E+06	2.238E+02				
1.995E+06	1.758E+02				
2.511E+06	1.378E+02				
3.162E+06	1.068E+02				
3.981E+06	8.168E+01				
5.011E+06	6.138E+01				
6.309E+06	4.488E+01				
7.943E+06	3.178E+01				
1.000E+07	2.168E+01				
1.258E+07	1.428E+01				
1.584E+07	9.198E+00				
1.995E+07	5.868E+00				
2.511E+07	3.728E+00				
(A)	VP(9)	-2.000E+02	0.	1.000E+02	2.000E+02
9.999E+02	-3.998E+00				
1.258E+03	-5.018E+00				
1.584E+03	-6.308E+00				
1.995E+03	-7.928E+00				
2.511E+03	-9.938E+00				
3.162E+03	-1.248E+01				
3.981E+03	-1.558E+01				
5.011E+03	-1.928E+01				
6.309E+03	-2.378E+01				
7.943E+03	-2.908E+01				
9.999E+03	-3.498E+01				
1.258E+04	-4.138E+01				
1.584E+04	-4.798E+01				
1.995E+04	-5.448E+01				
2.511E+04	-6.048E+01				
3.162E+04	-6.588E+01				
3.981E+04	-7.048E+01				
5.011E+04	-7.448E+01				
6.309E+04	-7.768E+01				
7.943E+04	-8.038E+01				
1.000E+05	-8.268E+01				
1.258E+05	-8.458E+01				
1.584E+05	-8.618E+01				
1.995E+05	-8.748E+01				
2.511E+05	-8.878E+01				
3.162E+05	-8.998E+01				
3.981E+05	-9.118E+01				
5.011E+05	-9.238E+01				
6.309E+05	-9.378E+01				
7.943E+05	-9.538E+01				
1.000E+06	-9.728E+01				
1.258E+06	-9.948E+01				
1.584E+06	-1.028E+02				
1.995E+06	-1.058E+02				
2.511E+06	-1.098E+02				
3.162E+06	-1.148E+02				
3.981E+06	-1.208E+02				
5.011E+06	-1.278E+02				
6.309E+06	-1.358E+02				
7.943E+06	-1.448E+02				
1.000E+07	-1.538E+02				
1.258E+07	-1.618E+02				
1.584E+07	-1.688E+02				
1.995E+07	-1.758E+02				
2.511E+07	-1.798E+02				

9-23

CMOS AMP WITH FB, EXPECT PHASE MARGIN = 80 DEGREES

VDD 1 0 5V

VSS 2 0 -5V

M1 7 5 4 4 P W=100U L=6.4U

M2 8 6 4 4 P W=100U L=6.4U

M3 7 7 2 2 N_50U W=50U L=6.4U

M4 8 7 2 2 N_50U W=50U L=6.4U

M5 4 3 1 1 P W=100U L=6.4U

M7 9 3 1 1 P W=100U L=6.4U

M8 3 3 1 1 P W=100U L=6.4U

M6 9 8 2 2 N_100U W=100U L=6.4U

IBIAS 3 2 20UA

RL 9 5 1MEG

RX 5 0 3.22K

.MODEL N_50U NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313 TOX=400E-10

+ CGSO=350PF CGDO=350PF CBD=60PF CBS=60PF

.MODEL N_100U NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313 TOX=400E-10

+ CGSO=350PF CGDO=350PF CBD=118PF CBS=118PF

.MODEL P_PMOS KP=30.2U VTO=-0.7 LAMBDA=0.0156 TOX=400E-10

+ CGSO=350PF CGDO=350PF CBD=346PF CBS=346PF

VI2 6 0 0V AC PULSE 0V 0.39MV 0N 0N 0N 3U

.PLOT TRAN V(9)

.TRAN 0.01U 0.5U

.TF V(9) VI2

.PLOT AC V(9)

.AC DEC 10 100K 20MEG

.OPTIONS NOPAGE NOMOD

.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U

.WIDTH OUT=80

.OPTIONS SPICE

.OP

.END

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

+0:1 = 5.000E+00 0:2 = -5.000E+00 0:3 = 4.011E+00

+0:4 = 9.029E-01 0:5 = -4.758E-05 0:6 = 0.

+0:7 = -4.092E+00 0:8 = -4.102E+00 0:9 = -1.482E-02

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(9)/VI2 = 3.077E+02

INPUT RESISTANCE AT VI2 = 9.999E+19

OUTPUT RESISTANCE AT V(9) = 6.524E+03

***** AC ANALYSIS THOM= 27.000 TEMP= 27.000

FREQ	V(9)	0.	1.000E+02	2.000E+02	3.000E+02	4.000E+02
1.000E+05	3.07E+02					
1.258E+05	3.06E+02					
1.584E+05	3.05E+02					
1.995E+05	3.04E+02					
2.511E+05	3.03E+02					
3.162E+05	3.00E+02					
3.981E+05	2.96E+02					
5.011E+05	2.90E+02					
6.309E+05	2.81E+02					
7.943E+05	2.68E+02					
1.000E+06	2.51E+02					
1.258E+06	2.29E+02					
1.584E+06	2.03E+02					
1.995E+06	1.75E+02					
2.511E+06	1.46E+02					
3.162E+06	1.18E+02					
3.981E+06	9.27E+01					
5.011E+06	7.00E+01					
6.309E+06	5.08E+01					
7.943E+06	3.52E+01					
1.000E+07	2.33E+01					
1.258E+07	1.49E+01					
1.584E+07	9.36E+00					
1.995E+07	5.82E+00					
2.511E+07	3.63E+00					

***** TRANSIENT ANALYSIS

THOM= 27.000 TEMP= 27.000

TIME	V(9)	0.	5.000E-02	1.000E-01	1.500E-01
0.	-1.48E-02				
1.000E-08	-1.45E-02				
2.000E-08	-1.18E-02				
3.000E-08	-7.23E-03				
4.000E-08	-1.20E-03				
5.000E-08	5.68E-03				
6.000E-08	1.29E-02				
7.000E-08	2.01E-02				
8.000E-08	2.70E-02				
9.000E-08	3.36E-02				
1.000E-07	3.97E-02				
1.100E-07	4.53E-02				
1.200E-07	5.05E-02				
1.300E-07	5.53E-02				
1.400E-07	5.97E-02				
1.500E-07	6.36E-02				
1.600E-07	6.73E-02				
1.700E-07	7.06E-02				
1.800E-07	7.36E-02				
1.900E-07	7.63E-02				
2.000E-07	7.89E-02				
2.100E-07	8.12E-02				
2.200E-07	8.33E-02				
2.300E-07	8.52E-02				
2.400E-07	8.69E-02				
2.500E-07	8.85E-02				
2.600E-07	9.00E-02				
2.700E-07	9.13E-02				
2.800E-07	9.25E-02				
2.900E-07	9.36E-02				
3.000E-07	9.46E-02				
3.100E-07	9.55E-02				
3.200E-07	9.64E-02				
3.300E-07	9.71E-02				
3.400E-07	9.78E-02				
3.500E-07	9.85E-02				
3.600E-07	9.91E-02				
3.700E-07	9.96E-02				
3.800E-07	1.00E-01				
3.900E-07	1.01E-01				
4.000E-07	1.01E-01				
4.100E-07	1.01E-01				
4.200E-07	1.02E-01				
4.300E-07	1.02E-01				
4.400E-07	1.02E-01				
4.500E-07	1.02E-01				
4.600E-07	1.03E-01				
4.700E-07	1.03E-01				
4.800E-07	1.03E-01				
4.900E-07	1.03E-01				
5.000E-07	1.03E-01				

STEP RESPONSE SHOWS NO OVERSHOOT

CMOS AMP WITH FB, EXPECT PHASE MARGIN = 60 DEGREES

VDD 1 0 5V

VSS 2 0 -5V

M1 7 5 4 4 P W=100U L=6.4U

M2 8 6 4 4 P W=100U L=6.4U

M3 7 7 2 2 N_50U W=50U L=6.4U

M4 8 7 2 2 N_50U W=50U L=6.4U

M5 4 3 1 1 P W=100U L=6.4U

M7 9 3 1 1 P W=100U L=6.4U

M8 3 3 1 1 P W=100U L=6.4U

M6 9 8 2 2 N_100U W=100U L=6.4U

IBIAS 3 2 20UA

RL 9 5 1MEG

RX 5 0 11.2K

.MODEL N_50U NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313 TOX=400E-10

+ CGSO=350PF CGDO=350PF CBD=60PF CBS=60PF

.MODEL N_100U NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313 TOX=400E-10

+ CGSO=350PF CGDO=350PF CBD=118PF CBS=118PF

.MODEL P_PMOS KP=30.2U VTO=-0.7 LAMBDA=0.0156 TOX=400E-10

+ CGSO=350PF CGDO=350PF CBD=346PF CBS=346PF

VI2 6 0 0V AC PULSE 0V 1.11MV 0N 0N 0N 3U

.PLOT TRAN V(9)

.TRAN 0.01U 0.5U

.TF V(9) VI2

.PLOT AC V(9)

.AC DEC 10 100K 20MEG

.OPTIONS NOPAGE NOMOD

.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U

.WIDTH OUT=80

.OPTIONS SPICE

.OP

.END

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

9-24

V(9)/VI2 = 8.996E+01
 INPUT RESISTANCE AT VI2 = 9.999E+19
 OUTPUT RESISTANCE AT V(9) = 1.907E+03

***** AC ANALYSIS THOM= 27.000 TEMP= 27.000

FREQ	V(9)					
(A)		-5.000E+01	0.	5.000E+01	1.000E+02	1.500E+02
1.000E+05	8.99E+01	+	+	+	+	+
1.258E+05	8.99E+01	+	+	+	+	+
1.584E+05	8.99E+01	+	+	+	+	+
1.995E+05	8.99E+01	+	+	+	+	+
2.511E+05	8.99E+01	+	+	+	+	+
3.162E+05	9.00E+01	+	+	+	+	+
3.981E+05	9.00E+01	+	+	+	+	+
5.011E+05	9.00E+01	+	+	+	+	+
6.309E+05	9.01E+01	+	+	+	+	+
7.943E+05	9.02E+01	+	+	+	+	+
1.000E+06	9.03E+01	+	+	+	+	+
1.258E+06	9.05E+01	+	+	+	+	+
1.584E+06	9.08E+01	+	+	+	+	+
1.995E+06	9.13E+01	+	+	+	+	+
2.511E+06	9.19E+01	+	+	+	+	+
3.162E+06	9.24E+01	+	+	+	+	+
3.981E+06	9.18E+01	+	+	+	+	+
5.011E+06	8.66E+01	+	+	+	+	+
6.309E+06	7.15E+01	+	+	+	+	+
7.943E+06	4.86E+01	+	+	+	+	+
1.000E+07	2.89E+01	+	+	+	+	+
1.258E+07	1.64E+01	+	+	+	+	+
1.584E+07	9.29E+00	+	+	+	+	+
1.995E+07	5.32E+00	+	+	+	+	+
2.511E+07	3.12E+00	+	+	+	+	+

***** TRANSIENT ANALYSIS THOM= 27.000 TEMP= 27.000

TIME	V(9)					
(A)		-5.000E-02	0.	5.000E-02	1.000E-01	1.500E-01
0.	-4.33E-03	+	+	+	+	+
1.000E-08	-3.57E-03	+	+	+	+	+
2.000E-08	3.14E-03	+	+	+	+	+
3.000E-08	1.48E-02	+	+	+	+	+
4.000E-08	3.03E-02	+	+	+	+	+
5.000E-08	4.74E-02	+	+	+	+	+
6.000E-08	6.40E-02	+	+	+	+	+
7.000E-08	7.85E-02	+	+	+	+	+
8.000E-08	9.00E-02	+	+	+	+	+
9.000E-08	9.81E-02	+	+	+	+	+
1.000E-07	1.03E-01	+	+	+	+	+
1.100E-07	1.05E-01	+	+	+	+	+
1.200E-07	1.06E-01	+	+	+	+	+
1.300E-07	1.04E-01	+	+	+	+	+
1.400E-07	1.02E-01	+	+	+	+	+
1.500E-07	1.00E-01	+	+	+	+	+
1.600E-07	9.83E-02	+	+	+	+	+
1.700E-07	9.65E-02	+	+	+	+	+
1.800E-07	9.52E-02	+	+	+	+	+
1.900E-07	9.44E-02	+	+	+	+	+
2.000E-07	9.40E-02	+	+	+	+	+
2.100E-07	9.39E-02	+	+	+	+	+
2.200E-07	9.41E-02	+	+	+	+	+
2.300E-07	9.44E-02	+	+	+	+	+
2.400E-07	9.47E-02	+	+	+	+	+
2.500E-07	9.50E-02	+	+	+	+	+
2.600E-07	9.53E-02	+	+	+	+	+
2.700E-07	9.55E-02	+	+	+	+	+
2.800E-07	9.57E-02	+	+	+	+	+
2.900E-07	9.57E-02	+	+	+	+	+
3.000E-07	9.58E-02	+	+	+	+	+
3.100E-07	9.58E-02	+	+	+	+	+
3.200E-07	9.57E-02	+	+	+	+	+
3.300E-07	9.57E-02	+	+	+	+	+
3.400E-07	9.56E-02	+	+	+	+	+
3.500E-07	9.56E-02	+	+	+	+	+
3.600E-07	9.55E-02	+	+	+	+	+
3.700E-07	9.55E-02	+	+	+	+	+
3.800E-07	9.55E-02	+	+	+	+	+
3.900E-07	9.55E-02	+	+	+	+	+
4.000E-07	9.55E-02	+	+	+	+	+
4.100E-07	9.55E-02	+	+	+	+	+
4.200E-07	9.55E-02	+	+	+	+	+
4.300E-07	9.55E-02	+	+	+	+	+
4.400E-07	9.55E-02	+	+	+	+	+
4.500E-07	9.55E-02	+	+	+	+	+
4.600E-07	9.55E-02	+	+	+	+	+
4.700E-07	9.55E-02	+	+	+	+	+
4.800E-07	9.55E-02	+	+	+	+	+
4.900E-07	9.55E-02	+	+	+	+	+
5.000E-07	9.55E-02	+	+	+	+	+

STEP RESPONSE SHOWS SLIGHT OVERSHOOT

CMOS AMP WITH FB, EXPECT PHASE MARGIN = 45 DEGREES

VDD 1 0 5V
 VSS 2 0 -5V
 M1 7 5 4 4 P W=100U L=6.4U
 M2 8 6 4 4 P W=100U L=6.4U
 M3 7 7 2 2 N_50U W=50U L=6.4U
 M4 8 7 2 2 N_50U W=50U L=6.4U
 M5 4 3 1 1 P W=100U L=6.4U
 M7 9 3 1 1 P W=100U L=6.4U
 M8 3 3 1 1 P W=100U L=6.4U
 M6 9 8 2 2 N_100U W=100U L=6.4U
 IBIAS 3 2 20UA
 RL 9 5 1MEG
 RX 5 0 20.5K

.MODEL N_50U NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313 TOX=400E-10
 + CGSO=350PF CGDO=350PF CBD=60FF CBS=60FF
 .MODEL N_100U NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313 TOX=400E-10
 + CGSO=350PF CGDO=350PF CBD=118FF CBS=118FF
 .MODEL P PMOS KP=30.2U VTO=-0.7 LAMBDA=0.0156 TOX=400E-10
 + CGSO=350PF CGDO=350PF CBD=346FF CBS=346FF
 VI2 6 0 0V AC PULSE 0V 2MV ON ON ON 3U
 .PLOT TRAN V(9)
 .TRAN 0.01U 0.5U
 .TF V(9) VI2
 .PLOT AC V(9)
 .AC DEC 10 100K 20MEG
 .OPTIONS NOPAGE NOMOD
 .OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
 .WIDTH OUT=80
 .OPTIONS SPICE
 .OP
 .END

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(9)/VI2 = 4.968E+01
 INPUT RESISTANCE AT VI2 = 9.999E+19
 OUTPUT RESISTANCE AT V(9) = 1.053E+03

***** AC ANALYSIS THOM= 27.000 TEMP= 27.000

FREQ	V(9)					
(A)		-5.000E+01	0.	5.000E+01	1.000E+02	1.500E+02
1.000E+05	4.96E+01	+	+	+	+	+
1.258E+05	4.96E+01	+	+	+	+	+
1.584E+05	4.97E+01	+	+	+	+	+
1.995E+05	4.97E+01	+	+	+	+	+
2.511E+05	4.97E+01	+	+	+	+	+
3.162E+05	4.97E+01	+	+	+	+	+
3.981E+05	4.97E+01	+	+	+	+	+
5.011E+05	4.98E+01	+	+	+	+	+
6.309E+05	4.98E+01	+	+	+	+	+
7.943E+05	5.00E+01	+	+	+	+	+
1.000E+06	5.01E+01	+	+	+	+	+
1.258E+06	5.05E+01	+	+	+	+	+
1.584E+06	5.10E+01	+	+	+	+	+
1.995E+06	5.18E+01	+	+	+	+	+
2.511E+06	5.32E+01	+	+	+	+	+
3.162E+06	5.57E+01	+	+	+	+	+
3.981E+06	6.05E+01	+	+	+	+	+
5.011E+06	7.04E+01	+	+	+	+	+
6.309E+06	9.10E+01	+	+	+	+	+
7.943E+06	8.84E+01	+	+	+	+	+
1.000E+07	3.88E+01	+	+	+	+	+
1.258E+07	1.71E+01	+	+	+	+	+
1.584E+07	8.35E+00	+	+	+	+	+
1.995E+07	4.36E+00	+	+	+	+	+
2.511E+07	2.47E+00	+	+	+	+	+

9-25

***** TRANSIENT ANALYSIS THOM= 27.000 TEMP= 27.000

TIME	V(9)				
(A)		-5.000E-02	0.	5.000E-02	1.000E-01
0.	-2.39E-03				
1.000E-08	-1.22E-03				
2.000E-08	9.46E-03				
3.000E-08	2.82E-02				
4.000E-08	5.34E-02				
5.000E-08	8.08E-02				
6.000E-08	1.06E-01				
7.000E-08	1.24E-01				
8.000E-08	1.33E-01				
9.000E-08	1.34E-01				
1.000E-07	1.27E-01				
1.100E-07	1.15E-01				
1.200E-07	1.02E-01				
1.300E-07	9.98E-02				
1.400E-07	8.11E-02				
1.500E-07	7.70E-02				
1.600E-07	7.74E-02				
1.700E-07	8.16E-02				
1.800E-07	8.81E-02				
1.900E-07	9.52E-02				
2.000E-07	1.01E-01				
2.100E-07	1.06E-01				
2.200E-07	1.08E-01				
2.300E-07	1.07E-01				
2.400E-07	1.05E-01				
2.500E-07	1.01E-01				
2.600E-07	9.74E-02				
2.700E-07	9.42E-02				
2.800E-07	9.21E-02				
2.900E-07	9.13E-02				
3.000E-07	9.17E-02				
3.100E-07	9.31E-02				
3.200E-07	9.50E-02				
3.300E-07	9.70E-02				
3.400E-07	9.86E-02				
3.500E-07	9.97E-02				
3.600E-07	1.00E-01				
3.700E-07	9.97E-02				
3.800E-07	9.89E-02				
3.900E-07	9.79E-02				
4.000E-07	9.68E-02				
4.100E-07	9.60E-02				
4.200E-07	9.55E-02				
4.300E-07	9.54E-02				
4.400E-07	9.56E-02				
4.500E-07	9.60E-02				
4.600E-07	9.66E-02				
4.700E-07	9.71E-02				
4.800E-07	9.75E-02				
4.900E-07	9.78E-02				
5.000E-07	9.78E-02				

STEP RESPONSE SHOWS SIGNIFICANT OVERSHOOT AND LONG SETTLING TIME

CMOS AMP WITH FB, EXPECT PHASE MARGIN = 20 DEGREES

VDD 1 0 5V

VSS 2 0 -5V

M1 7 5 4 4 P W=100U L=6.4U

M2 8 6 4 4 P W=100U L=6.4U

M3 7 7 2 2 N_50U W=50U L=6.4U

M4 8 7 2 2 N_50U W=50U L=6.4U

M5 4 3 1 1 P W=100U L=6.4U

M7 9 3 1 1 P W=100U L=6.4U

M8 3 3 1 1 P W=100U L=6.4U

M6 9 8 2 2 N_100U W=100U L=6.4U

IBIAS 3 2 200A

RL 9 5 1MEG

RX 5 0 30K

.MODEL M_50U NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313 TOX=400E-10

+ CGSO=350PF CGDO=350PF CBD=60PF CBS=60PF

.MODEL M_100U NMOS KP=60.4U VTO=0.7 LAMBDA=0.0313 TOX=400E-10

+ CGSO=350PF CGDO=350PF CBD=118PF CBS=118PF

.MODEL P_PMOS KP=30.2U VTO=-0.7 LAMBDA=0.0156 TOX=400E-10

+ CGSO=350PF CGDO=350PF CBD=346PF CBS=346PF

V12 6 0 0V AC PULSE OV 2.92MV ON ON 3U

.PLOT TRAN V(9)

.TRAN 0.01U 1.5U

.TF V(9) V12

.PLOT AC V(9)

.AC DEC 10 100K 20MEG

.OPTIONS NOPAGE NOMOD

.OPTIONS VRTOL=1N ABSTOL=1F RELTOL=1U

.WIDTH OUT=80

.OPTIONS SPICE

.OP

.END

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(9)/V12 = 3.428E+01

INPUT RESISTANCE AT V12 = 9.999E+19
OUTPUT RESISTANCE AT V(9) = 7.270E+02

***** AC ANALYSIS THOM= 27.000 TEMP= 27.000

FREQ	V(9)				
(A)		0.	1.000E+02	2.000E+02	3.000E+02
1.000E+05	3.42E+01				
1.258E+05	3.42E+01				
1.584E+05	3.42E+01				
1.995E+05	3.43E+01				
2.511E+05	3.43E+01				
3.162E+05	3.43E+01				
3.981E+05	3.43E+01				
5.011E+05	3.43E+01				
6.309E+05	3.44E+01				
7.943E+05	3.44E+01				
1.000E+06	3.45E+01				
1.258E+06	3.47E+01				
1.584E+06	3.50E+01				
1.995E+06	3.55E+01				
2.511E+06	3.64E+01				
3.162E+06	3.79E+01				
3.981E+06	4.10E+01				
5.011E+06	4.77E+01				
6.309E+06	6.82E+01				
7.943E+06	2.76E+02				
1.000E+07	4.98E+01				
1.258E+07	1.58E+01				
1.584E+07	6.94E+00				
1.995E+07	3.51E+00				
2.511E+07	2.06E+00				

***** TRANSIENT ANALYSIS THOM= 27.000 TEMP= 27.000

TIME	V(9)				
(A)		-1.000E-01	0.	1.000E-01	2.000E-01
0.	-1.65E-03				
1.000E-08	-1.13E-04				
2.000E-08	1.41E-02				
3.000E-08	3.91E-02				
4.000E-08	7.18E-02				
5.000E-08	1.03E-01				
6.000E-08	1.32E-01				
7.000E-08	1.54E-01				
8.000E-08	1.57E-01				
9.000E-08	1.55E-01				
1.000E-07	1.32E-01				
1.100E-07	1.09E-01				
1.200E-07	8.04E-02				
1.300E-07	5.58E-02				
1.400E-07	4.59E-02				
1.500E-07	4.07E-02				
1.600E-07	5.63E-02				
1.700E-07	7.39E-02				
1.800E-07	1.01E-01				
1.900E-07	1.25E-01				
2.000E-07	1.41E-01				
2.100E-07	1.53E-01				
2.200E-07	1.44E-01				
2.300E-07	1.34E-01				
2.400E-07	1.10E-01				
2.500E-07	8.67E-02				
2.600E-07	6.80E-02				
2.700E-07	5.15E-02				
2.800E-07	5.33E-02				
2.900E-07	5.67E-02				
3.000E-07	7.63E-02				
3.100E-07	9.60E-02				
3.200E-07	1.16E-01				
3.300E-07	1.35E-01				
3.400E-07	1.39E-01				
3.500E-07	1.43E-01				
3.600E-07	1.28E-01				
3.700E-07	1.13E-01				
3.800E-07	9.28E-02				
3.900E-07	7.28E-02				
4.000E-07	6.42E-02				
4.100E-07	5.57E-02				
4.200E-07	6.52E-02				
4.300E-07	7.47E-02				
4.400E-07	9.33E-02				
4.500E-07	1.12E-01				
4.600E-07	1.24E-01				
4.700E-07	1.36E-01				
4.800E-07	1.32E-01				
4.900E-07	1.28E-01				
5.000E-07	1.12E-01				
5.100E-07	9.61E-02				
5.200E-07	8.19E-02				
5.300E-07	6.79E-02				
5.400E-07	6.67E-02				
5.500E-07	6.65E-02				
5.600E-07	7.83E-02				
5.700E-07	9.12E-02				

5.800E-07	1.06E-01	+	+	+	+	A	+	+	+	+
5.900E-07	1.20E-01	+	+	+	+	A	+	+	+	+
6.000E-07	1.26E-01	+	+	+	+	A	+	+	+	+
6.100E-07	1.30E-01	+	+	+	+	A	+	+	+	+
6.200E-07	1.22E-01	+	+	+	+	A	+	+	+	+
6.300E-07	1.13E-01	+	+	+	+	A	+	+	+	+
6.400E-07	9.96E-02	+	+	+	+	A	+	+	+	+
6.500E-07	8.53E-02	+	+	+	+	A	+	+	+	+
6.600E-07	7.70E-02	+	+	+	+	A	+	+	+	+
6.700E-07	6.98E-02	+	+	+	+	A	+	+	+	+
6.800E-07	7.32E-02	+	+	+	+	A	+	+	+	+
6.900E-07	7.87E-02	+	+	+	+	A	+	+	+	+
7.000E-07	9.03E-02	+	+	+	+	A	+	+	+	+
7.100E-07	1.03E-01	+	+	+	+	A	+	+	+	+
7.200E-07	1.13E-01	+	+	+	+	A	+	+	+	+
7.300E-07	1.22E-01	+	+	+	+	A	+	+	+	+
7.400E-07	1.23E-01	+	+	+	+	A	+	+	+	+
7.500E-07	1.21E-01	+	+	+	+	A	+	+	+	+
7.600E-07	1.12E-01	+	+	+	+	A	+	+	+	+
7.700E-07	1.01E-01	+	+	+	+	A	+	+	+	+
7.800E-07	9.07E-02	+	+	+	+	A	+	+	+	+
7.900E-07	8.03E-02	+	+	+	+	A	+	+	+	+
8.000E-07	7.68E-02	+	+	+	+	A	+	+	+	+
8.100E-07	7.56E-02	+	+	+	+	A	+	+	+	+
8.200E-07	8.14E-02	+	+	+	+	A	+	+	+	+
8.300E-07	8.98E-02	+	+	+	+	A	+	+	+	+
8.400E-07	9.97E-02	+	+	+	+	A	+	+	+	+
8.500E-07	1.10E-01	+	+	+	+	A	+	+	+	+
8.600E-07	1.16E-01	+	+	+	+	A	+	+	+	+
8.700E-07	1.20E-01	+	+	+	+	A	+	+	+	+
8.800E-07	1.17E-01	+	+	+	+	A	+	+	+	+
8.900E-07	1.11E-01	+	+	+	+	A	+	+	+	+
9.000E-07	1.03E-01	+	+	+	+	A	+	+	+	+
9.100E-07	9.29E-02	+	+	+	+	A	+	+	+	+
9.200E-07	8.57E-02	+	+	+	+	A	+	+	+	+
9.300E-07	7.99E-02	+	+	+	+	A	+	+	+	+
9.400E-07	7.99E-02	+	+	+	+	A	+	+	+	+
9.500E-07	8.29E-02	+	+	+	+	A	+	+	+	+
9.600E-07	8.96E-02	+	+	+	+	A	+	+	+	+
9.700E-07	9.84E-02	+	+	+	+	A	+	+	+	+
9.800E-07	1.06E-01	+	+	+	+	A	+	+	+	+
9.900E-07	1.13E-01	+	+	+	+	A	+	+	+	+
1.000E-06	1.15E-01	+	+	+	+	A	+	+	+	+
1.010E-06	1.15E-01	+	+	+	+	A	+	+	+	+
1.020E-06	1.10E-01	+	+	+	+	A	+	+	+	+
1.030E-06	1.03E-01	+	+	+	+	A	+	+	+	+
1.040E-06	9.58E-02	+	+	+	+	A	+	+	+	+
1.050E-06	8.83E-02	+	+	+	+	A	+	+	+	+
1.060E-06	8.41E-02	+	+	+	+	A	+	+	+	+
1.070E-06	8.25E-02	+	+	+	+	A	+	+	+	+
1.080E-06	8.40E-02	+	+	+	+	A	+	+	+	+
1.090E-06	9.01E-02	+	+	+	+	A	+	+	+	+
1.100E-06	9.66E-02	+	+	+	+	A	+	+	+	+
1.110E-06	1.04E-01	+	+	+	+	A	+	+	+	+
1.120E-06	1.09E-01	+	+	+	+	A	+	+	+	+
1.130E-06	1.13E-01	+	+	+	+	A	+	+	+	+
1.140E-06	1.13E-01	+	+	+	+	A	+	+	+	+
1.150E-06	1.09E-01	+	+	+	+	A	+	+	+	+
1.160E-06	1.04E-01	+	+	+	+	A	+	+	+	+
1.170E-06	9.71E-02	+	+	+	+	A	+	+	+	+
1.180E-06	9.13E-02	+	+	+	+	A	+	+	+	+
1.190E-06	8.68E-02	+	+	+	+	A	+	+	+	+
1.200E-06	8.52E-02	+	+	+	+	A	+	+	+	+
1.210E-06	8.67E-02	+	+	+	+	A	+	+	+	+
1.220E-06	9.03E-02	+	+	+	+	A	+	+	+	+
1.230E-06	9.62E-02	+	+	+	+	A	+	+	+	+
1.240E-06	1.02E-01	+	+	+	+	A	+	+	+	+
1.250E-06	1.07E-01	+	+	+	+	A	+	+	+	+
1.260E-06	1.10E-01	+	+	+	+	A	+	+	+	+
1.270E-06	1.10E-01	+	+	+	+	A	+	+	+	+
1.280E-06	1.08E-01	+	+	+	+	A	+	+	+	+
1.290E-06	1.04E-01	+	+	+	+	A	+	+	+	+
1.300E-06	9.87E-02	+	+	+	+	A	+	+	+	+
1.310E-06	9.32E-02	+	+	+	+	A	+	+	+	+
1.320E-06	8.93E-02	+	+	+	+	A	+	+	+	+
1.330E-06	8.76E-02	+	+	+	+	A	+	+	+	+
1.340E-06	8.79E-02	+	+	+	+	A	+	+	+	+
1.350E-06	9.12E-02	+	+	+	+	A	+	+	+	+
1.360E-06	9.53E-02	+	+	+	+	A	+	+	+	+
1.370E-06	1.01E-01	+	+	+	+	A	+	+	+	+
1.380E-06	1.05E-01	+	+	+	+	A	+	+	+	+
1.390E-06	1.08E-01	+	+	+	+	A	+	+	+	+
1.400E-06	1.09E-01	+	+	+	+	A	+	+	+	+
1.410E-06	1.07E-01	+	+	+	+	A	+	+	+	+
1.420E-06	1.04E-01	+	+	+	+	A	+	+	+	+
1.430E-06	9.92E-02	+	+	+	+	A	+	+	+	+
1.440E-06	9.49E-02	+	+	+	+	A	+	+	+	+
1.450E-06	9.14E-02	+	+	+	+	A	+	+	+	+
1.460E-06	8.92E-02	+	+	+	+	A	+	+	+	+
1.470E-06	8.98E-02	+	+	+	+	A	+	+	+	+
1.480E-06	9.14E-02	+	+	+	+	A	+	+	+	+
1.490E-06	9.54E-02	+	+	+	+	A	+	+	+	+
1.500E-06	9.96E-02	+	+	+	+	A	+	+	+	+

TRANSFER FUNCTION HAS PEAKING
 THE EXPECTED RX=66.3K CAUSES OSCILLATION
 (I.E. NEGATIVE PHASE MARGIN), BECAUSE WE DID NOT TAKE

INTO ACCOUNT THE PHASE CONTRIBUTION FROM THE POLE
 IN THE FEEDBACK PATH BY RX AND INPUT CAPACITANCE
 OF M1.

WE USE RX=30K HERE.

FINDING THE EXACT RX VALUE FOR THE PHASE MARGIN OF 20 DEGREES
 IS NOT AS IMPORTANT AS OBSERVING THIS GENERAL TREND:

THE SMALLER THE PHASE MARGIN,
 THE HIGHER THE OVERSHOOT & THE LONGER THE SETTLING TIME
 IN THE STEP RESPONSE.

9.28

dc bias

$$I_D = 20 \mu A = I_1$$

in all devices

gain

$$A_V = G_m R_o$$

$$g_{m3} = \sqrt{2 k_n' \frac{W}{L} I_3}$$

$$= \sqrt{2 (60 \mu) \left(\frac{20}{1} \right) (20 \mu)}$$

$$= 219 \mu A/V$$

$$g_{m6} = \sqrt{2 (20 \mu) \left(\frac{60}{1} \right) (20 \mu)}$$

$$= 219 \mu A/V$$

$$V_{GS3} = \sqrt{\frac{2 I_3}{k_n' \left(\frac{W}{L} \right)_3}} + V_{t3}$$

$$|V_{GS6}| = \sqrt{\frac{2 I_6}{k_p' \left(\frac{W}{L} \right)_6}} + |V_{t6}|$$

$$V_{t3} = |V_{t6}|$$

$$k_n' \left(\frac{W}{L} \right)_3 = k_p' \left(\frac{W}{L} \right)_6$$

$$\mu_n C_{ox} \left(\frac{W}{L} \right)_n = \mu_p C_{ox} \left(\frac{W}{L} \right)_p$$

$$\therefore V_{GS3} = |V_{GS6}|$$

$\therefore m_3$ & m_6 share V_i equally

$$\therefore A_V = G_m R_o$$

$$= g_{m3} (R_{o14} \parallel R_{o15})$$

$$g_{m14} = \sqrt{2 (20 \mu) \left(\frac{300 \mu}{1} \right) (20 \mu)}$$

$$= 490 \mu A/V$$

$$g_{m15} = \sqrt{2 (60 \mu) \left(\frac{100}{1} \right) (20 \mu)}$$

$$= 490 \mu A/V$$

$$R_{o14} = r_{o14} (1 + g_{m14} r_{o13})$$

$$= 1 M (1 + 490 \mu 1 M)$$

$$= 491 M$$

$$r_{o14} = r_{o13} = \frac{1}{\lambda I_D}$$

$$= \frac{1}{0.05 (20 \mu)} = 1 M$$

9.27

$$R_{o14} \parallel R_{o15} = 245 M$$

$$A_V = g_{m3} (245 M)$$

$$= 219 \mu (245 M)$$

$$= 53700$$

high freq gain

$$A_V = g_{m3} \frac{1}{j \omega C_L}$$

$$|A_V| = 1 = \frac{g_{m3}}{\omega C_L}$$

$$\text{unity gain } \omega_1 = \frac{g_{m3}}{C_L} = \frac{219 \mu}{10 p}$$

$$= 21.9 M \text{ rad/s}$$

$$\hookrightarrow 3.5 \text{ MHz}$$

unity gain freq

 m_2, m_3, m_6, m_7 on

$$I_o = |I_{14}| - I_{15} = |I_{10}| - I_{11}$$

$$= I_3 - |I_7|$$

$$= \frac{\mu_n C_{ox} \left(\frac{W}{L} \right)_3}{2} (V_{GS3 \text{ bias}} + \frac{V_i}{2} - V_{t3})^2$$

$$- \frac{\mu_p C_{ox} \left(\frac{W}{L} \right)_7}{2} (V_{GS7 \text{ bias}} - \frac{V_i}{2} - V_{t7})^2$$

$$= \frac{\mu_n C_{ox} \left(\frac{W}{L} \right)_3}{2} \left(2 \frac{V_i}{2} (V_{GS3 \text{ bias}} - V_{t3}) \right.$$

$$\left. - 2 \frac{V_i}{2} (V_{GS7 \text{ bias}} - V_{t7}) \right)$$

$$I_o = \mu_n C_{ox} \left(\frac{W}{L} \right)_3 (V_{GS3 \text{ bias}} - V_{t3}) V_i$$

$$= g_{m3} V_i$$

$$= (219 \mu A/V) V_i$$

linear relation

$$G_m = \frac{I_o}{V_i} = g_{m3}$$

$$\mu_n C_{ox} \left(\frac{W}{L} \right)_3 = \mu_p C_{ox} \left(\frac{W}{L} \right)_7$$

$$V_{t3} = V_{t7}$$

$$V_{GS3 \text{ bias}} = V_{GS7 \text{ bias}}$$

9-28

m_2, m_7 cut off

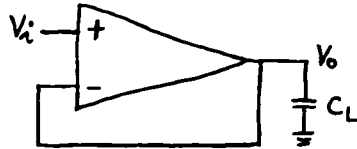
$$I_7 = 0 \text{ for } V_{GS7\text{bias}} - V_{t7} \leq \frac{V_i}{2}$$

$$2(V_{GS\text{bias}} - V_{t7}) \leq V_i$$

$$2 \sqrt{\frac{2 I_7}{\mu_p C_{ox} \left(\frac{W}{L}\right)_7}} = 0.365 \text{ V} \leq V_i$$

$$I_0 = I_3 = \frac{1}{2} \mu_n C_{ox} \left(\frac{W}{L}\right)_3 (V_{GS3\text{bias}} + \frac{V_i}{2} - V_t)^2$$

square relation

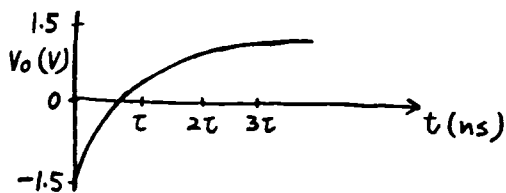


$$\frac{V_o}{V_i} = \frac{1}{1 + s\tau}$$

$$\tau = \frac{1}{\omega_i} = \frac{1}{21.9 \text{ M rad/s}} = 45.7 \text{ ns}$$

↑
unity gain freq

$$V_o = -1.5 + 3(1 - e^{-\frac{t}{45.7 \text{ ns}}})$$



t	V_o
45.7 ns (1τ)	0.4 V
91.4 ns (2τ)	1.1 V
137 ns (3τ)	1.4 V

peak current to C_L

$$\Delta V_i = 3 \text{ V}$$

$$I_{D3} = \frac{\mu_n C_{ox} \left(\frac{W}{L}\right)_3}{2} (V_{GS3\text{bias}} + \frac{\Delta V_i}{2} - V_t)^2$$

$$= \frac{60 \mu \text{A}}{2} \frac{20}{1} (0.183 + 1.5)^2$$

$$= 1.7 \text{ mA}$$

$$V_{GS3\text{bias}} - V_t = \sqrt{\frac{2 I_3}{\mu_n C_{ox} \left(\frac{W}{L}\right)_3}} = 0.183 \text{ V}$$

CROSS-COUPLED MOS QUAD

```

VDD 1 0 5V
VSS 2 0 -5V
M1 1 19 5 2 N W=20U L=1U
M2 1 19 7 2 N W=20U L=1U
M3 14 4 8 2 N W=20U L=1U
M4 1 4 6 2 N W=20U L=1U
M5 9 9 5 1 P W=60U L=1U
M6 2 9 8 1 P W=60U L=1U
M7 11 12 7 1 P W=60U L=1U
M8 12 12 6 1 P W=60U L=1U
M11 11 11 17 2 N W=100U L=1U
M12 17 17 2 2 N W=100U L=1U
M15 19 11 18 2 N W=100U L=1U
M16 18 17 2 2 N W=100U L=1U
M9 15 15 1 1 P W=300U L=1U
M10 14 14 15 1 P W=300U L=1U
M13 16 15 1 1 P W=300U L=1U
M14 29 14 16 1 P W=300U L=1U
VDUMY 29 19 0V
IBIAS1 9 2 20VA
IBIAS2 12 2 20VA
CL 19 0 10PF
.MODEL N NMOS KP=60U VTO=0.7 LAMBDA=0.05
.MODEL P PMOS KP=20U VTO=-0.7 LAMBDA=0.05
VI2 4 0 PULSE -1.5 1.5 0N 0N 3US
.PLOT TRAN V(19)
.PLOT TRAN I(VDUMY)
.TRAM 0.005U 0.25U
.OPTIONS NOPAGE NOMOD
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

```

+0:1 = 5.000E+00 0:2 =-5.000E+00 0:4 =-1.500E+00
+0:5 =-2.355E+00 0:6 =-2.356E+00 0:7 =-2.356E+00
+0:8 =-2.361E+00 0:9 =-3.234E+00 0:11 =-3.439E+00
+0:12 =-3.234E+00 0:14 = 3.439E+00 0:15 = 4.219E+00
+0:16 = 4.211E+00 0:17 =-4.219E+00 0:18 =-4.216E+00
+0:19 =-1.499E+00 0:29 =-1.499E+00

```

**** MOSFETS

ELEMENT	0:M1	0:M2	0:M3	0:M4	0:M5	0:M6
MODEL	0:N	0:N	0:N	0:N	0:P	0:P
ID	2.000E-05	2.020E-05	2.020E-05	2.000E-05	-2.000E-05	-2.020E-05
IBS	-2.645E-14	-2.644E-14	-2.638E-14	-2.644E-14	7.355E-14	7.362E-14
IBD	-1.000E-13	-1.000E-13	-8.439E-14	-1.000E-13	8.234E-14	1.000E-13
VGS	8.561E-01	8.569E-01	8.615E-01	8.561E-01	-8.787E-01	-8.725E-01
VDS	7.355E+00	7.356E+00	5.800E+00	7.356E+00	-8.787E-01	-2.638E+00
VBS	-2.644E+00	-2.643E+00	-2.638E+00	-2.643E+00	7.355E+00	7.361E+00
VTH	7.000E-01	7.000E-01	7.000E-01	7.000E-01	-7.000E-01	-7.000E-01
VDSAT	1.561E-01	1.569E-01	1.615E-01	1.561E-01	-1.787E-01	-1.725E-01
BETA	1.641E-03	1.641E-03	1.548E-03	1.641E-03	1.253E-03	1.358E-03
GAM EFF	0.	0.	0.	0.	0.	0.
GM	2.562E-04	2.575E-04	2.501E-04	2.562E-04	2.239E-04	2.342E-04
GDS	7.311E-07	7.385E-07	7.828E-07	7.311E-07	9.579E-07	8.922E-07
GMB	0.	0.	0.	0.	0.	0.
CDTOT	0.	0.	0.	0.	0.	0.
CGTOT	0.	0.	0.	0.	0.	0.
CSTOT	0.	0.	0.	0.	0.	0.
CBTOT	0.	0.	0.	0.	0.	0.
CGS	0.	0.	0.	0.	0.	0.
CGD	0.	0.	0.	0.	0.	0.

ELEMENT	0:M7	0:M8	0:M11	0:M12	0:M15	0:M16
MODEL	0:P	0:P	0:N	0:N	0:N	0:N
ID	-2.020E-05	-2.000E-05	2.020E-05	2.020E-05	2.021E-05	2.021E-05
IBS	7.356E-14	7.356E-14	-7.805E-15	0.	-7.840E-15	0.
IBD	8.439E-14	8.235E-14	-1.561E-14	-7.805E-15	-3.501E-14	-7.840E-15
VGS	-8.787E-01	-8.787E-01	7.805E-01	7.805E-01	7.770E-01	7.805E-01
VDS	-1.082E+00	-8.787E-01	7.805E-01	7.805E-01	2.716E+00	7.840E-01
VBS	7.356E+00	7.356E+00	-7.805E-01	0.	-7.840E-01	0.
VTH	-7.000E-01	-7.000E-01	7.000E-01	7.000E-01	7.000E-01	7.000E-01
VDSAT	-1.787E-01	-1.787E-01	8.050E-02	8.050E-02	7.700E-02	8.050E-02
BETA	1.265E-03	1.253E-03	6.234E-03	6.234E-03	6.815E-03	6.235E-03
GAM EFF	0.	0.	0.	0.	0.	0.
GM	2.261E-04	2.239E-04	5.019E-04	5.019E-04	5.248E-04	5.020E-04
GDS	9.582E-07	9.579E-07	9.722E-07	9.722E-07	8.894E-07	9.722E-07
GMB	0.	0.	0.	0.	0.	0.
CDTOT	0.	0.	0.	0.	0.	0.
CGTOT	0.	0.	0.	0.	0.	0.
CSTOT	0.	0.	0.	0.	0.	0.
CBTOT	0.	0.	0.	0.	0.	0.
CGS	0.	0.	0.	0.	0.	0.
CGD	0.	0.	0.	0.	0.	0.

ELEMENT	0:M9	0:M10	0:M13	0:M14
MODEL	0:P	0:P	0:P	0:P
ID	-2.020E-05	-2.020E-05	-2.021E-05	-2.021E-05
IBS	0.	7.805E-15	0.	7.886E-15
IBD	7.805E-15	1.561E-14	7.886E-15	6.499E-14
VGS	-7.805E-01	-7.805E-01	-7.805E-01	-7.724E-01
VDS	-7.805E-01	-7.805E-01	-7.886E-01	-5.710E+00

VBS	0.	7.805E-01	0.	7.886E-01
VTH	-7.000E-01	-7.000E-01	-7.000E-01	-7.000E-01
VDSAT	-8.050E-02	-8.050E-02	-8.050E-02	-7.238E-02
BETA	6.234E-03	6.234E-03	6.237E-03	7.713E-03
GAM EFF	0.	0.	0.	0.
GM	5.018E-04	5.018E-04	5.020E-04	5.583E-04
GDS	9.719E-07	9.719E-07	9.719E-07	7.859E-07
GMB	0.	0.	0.	0.
CDTOT	0.	0.	0.	0.
CGTOT	0.	0.	0.	0.
CSTOT	0.	0.	0.	0.
CBTOT	0.	0.	0.	0.
CGS	0.	0.	0.	0.
CGD	0.	0.	0.	0.

***** TRANSIENT ANALYSIS

TNOM= 27.000 TEMP= 27.000

TIME	V(19)					
(A)	-2.000E+00	-1.000E-00	0.	1.000E-00	2.000E+00	
0.	-1.49E+00	-A				
5.000E-09	-1.17E+00	+ A				
1.000E-08	-5.48E-01	+ A				
1.500E-08	-1.21E-01	+ A				
2.000E-08	1.75E-01	+ A				
2.500E-08	3.94E-01	+ A				
3.000E-08	5.61E-01	+ A				
3.500E-08	6.94E-01	+ A				
4.000E-08	8.02E-01	+ A				
4.500E-08	8.92E-01	+ A				
5.000E-08	9.67E-01	-A				
5.500E-08	1.03E+00	+ A				
6.000E-08	1.08E+00	+ A				
6.500E-08	1.13E+00	+ A				
7.000E-08	1.17E+00	+ A				
7.500E-08	1.21E+00	+ A				
8.000E-08	1.24E+00	+ A				
8.500E-08	1.27E+00	+ A				
9.000E-08	1.30E+00	+ A				
9.500E-08	1.32E+00	+ A				
1.000E-07	1.34E+00	-A				
1.050E-07	1.36E+00	+ A				
1.100E-07	1.38E+00	+ A				
1.150E-07	1.39E+00	+ A				
1.200E-07	1.40E+00	+ A				
1.250E-07	1.41E+00	+ A				
1.300E-07	1.42E+00	+ A				
1.350E-07	1.43E+00	+ A				
1.400E-07	1.44E+00	+ A				
1.450E-07	1.45E+00	+ A				
1.500E-07	1.45E+00	-A				
1.550E-07	1.46E+00	+ A				
1.600E-07	1.46E+00	+ A				
1.650E-07	1.47E+00	+ A				
1.700E-07	1.47E+00	+ A				
1.750E-07	1.47E+00	+ A				
1.800E-07	1.47E+00	+ A				
1.850E-07	1.48E+00	+ A				
1.900E-07	1.48E+00	+ A				
1.950E-07	1.48E+00	+ A				
2.000E-07	1.48E+00	-A				

TIME	I(VDUMY)					
(A)	0.	5.000E-04	1.000E-03	1.500E-03	2.000E-03	
0.	2.02E-05	-A				
5.000E-09	1.61E-03	+ A				
1.000E-08	1.07E-03	+ A				
1.500E-08	6.89E-04	+ A				
2.000E-08	4.98E-04	+ A				
2.500E-08	3.76E-04	+ A				
3.000E-08	2.95E-04	+ A				
3.500E-08	2.37E-04	+ A				
4.000E-08	1.95E-04	+ A				
4.500E-08	1.63E-04	+ A				
5.000E-08	1.38E-04	-A				
5.500E-08	1.19E-04	+ A				
6.000E-08	1.03E-04	+ A				
6.500E-08	9.05E-05	+ A				
7.000E-08	8.00E-05	+ A				
7.500E-08	7.13E-05	+ A				
8.000E-08	6.40E-05	+ A				
8.500E-08	5.78E-05	+ A				
9.000E-08	5.27E-05	+ A				
9.500E-08	4.83E-05	+ A				
1.000E-07	4.46E-05	-A				

9-29

 $\Delta V_o = \pm 1V$ into $R_L = 1k\Omega$ need $I_{Dg} > 1mA$ set $I_{Dg} \approx 2mA$ (say $1.6mA$)this lowers R_o run m_1, m_2, m_3 at low I_D

with no FB

$$r_{oa} = \frac{1}{g_{m8} + g_{mb8}} \approx \frac{1}{g_{m8}}$$

set $V_{GSg} \approx 2.5V$ bias m_2 & m_3 equally

$$\begin{aligned} V_{t8} &= V_{t0} + \gamma(\sqrt{V_{SB} + 2\phi_f} - \sqrt{2\phi_f}) \\ &= 0.7 + 0.5(\sqrt{5 + 0.6} - \sqrt{0.6}) \\ &= 1.5V \end{aligned}$$

$$I_{Dg} = \frac{\mu_n C_{ox}}{2} \frac{W}{L} (V_{GS} - V_t)^2$$

$$1.6mA = \frac{60\mu}{2} \frac{W}{L} (2.5 - 1.5)^2$$

$$53 = \left(\frac{W}{L}\right)_8 = \frac{159\mu}{3\mu}$$

$$g_{m8} = \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_t)$$

$$= 60\mu(53)(1)$$

$$= 3.18m$$

$$r_{oa} = \frac{1}{g_{m8}} = 315\Omega$$

$$R_o = \frac{r_{oa}}{1+T}$$

$$30 = \frac{315}{1+T}$$

$$T = 9.5$$

series shunt FB

$$T = \frac{R_2}{R_2 + R_1} \frac{g_{m2}}{2} (2r_{o2} \parallel r_{o3})$$

$$\text{gain} = A = 10 \approx \frac{R_2 + R_1}{R_2}$$

$$9.5 = \frac{1}{10} \frac{g_{m2}}{2} (2r_{o2} \parallel r_{o3})$$

$$190 = g_{m2} (2r_{o2} \parallel r_{o3})$$

for large r_{o3} , make L_3 large

9-30

$$r_{o2} = \frac{1}{\frac{I_{D2}}{L} \frac{\partial X_d}{\partial V_{DS}}}$$

$$g_{m2} = k(V_{GS} - V_t)$$

$$g_{m2} r_{o2} = \frac{2L_2}{(V_{GS} - V_t) \frac{\partial X_d}{\partial V_{DS}}}$$

need L_2 large, $(V_{GS2} - V_{t2})$ small

$$\text{if } g_{m2} r_{o2} = 200$$

$$200 = \frac{2L}{V_{GS} - V_t} \frac{1}{0.2\mu}$$

$$L_2 = 20(V_{GS2} - V_{t2})\mu$$

if $(V_{GS2} - V_{t2})$ is too small, g_{m2} is smallcan $\uparrow g_{m2}$ by $\uparrow W_2$ but cap $\uparrow \therefore \downarrow BW$

$$\text{if } (V_{GS2} - V_{t2}) = 0.2$$

$$L_2 = 4\mu$$

$$\text{set } L_2 = L_3 = 10\mu = L_1$$

$$g_{m2} (2r_{o2} \parallel r_{o3})$$

$$= \frac{2I_{D2}}{V_{GS2} - V_{t2}} \left(2 \frac{V_{A2}}{I_{D2}} \parallel \frac{V_{A3}}{I_{D2}} \right)$$

$$= \frac{2I_{D2}}{V_{GS2} - V_{t2}} \frac{2 \frac{V_{A2}}{I_{D2}} \frac{V_{A3}}{I_{D2}}}{2 \frac{V_{A2}}{I_{D2}} + \frac{V_{A3}}{I_{D2}}}$$

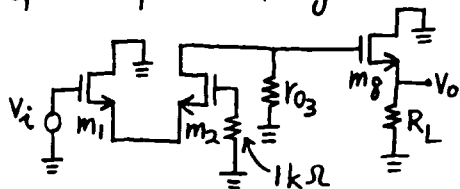
$$= \frac{2}{V_{GS2} - V_{t2}} \frac{2V_{A2} V_{A3}}{2V_{A2} + V_{A3}}$$

$$= \frac{2}{0.2} 50 = 500 > 190$$

$$V_{A2} = r_{o2} I_{D2} = \frac{L}{\frac{\partial X_d}{\partial V_{DS}}} = \frac{10\mu}{0.2\mu} = 50V$$

$$V_{A3} = \frac{10\mu}{0.1\mu} = 100V$$

open loop forward gain



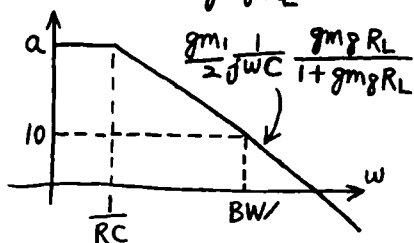
$$a = \frac{V_o}{V_i} \approx \frac{g_{m1}}{2} \underbrace{(2r_{o2} \parallel r_{o3})}_R \frac{g_{m8} R_L}{1 + g_{m8} R_L}$$

at high freq

$$a \approx \frac{g_{m1}}{2} \frac{R}{1 + sRC} \frac{g_{m8} R_L}{1 + g_{m8} R_L}$$

↑
dominant pole
at m_2 drain
by ZVTC

$$C = C_{dg2} + C_{db2} + C_{dg3} + C_{db3} + \frac{C_{gs8}}{1 + g_{m8} R_L}$$



↑ BW/ by ↑ g_{m1} & ↓ C

$$|G B| = \frac{g_{m1}}{2} R \frac{g_{m8} R_L}{1 + g_{m8} R_L} \frac{1}{RC}$$

$$10 \text{ BW/} = \frac{g_{m1}}{2} \frac{1}{C} \frac{g_{m8} R_L}{1 + g_{m8} R_L}$$

$$\begin{aligned} \text{BW/} &= \frac{g_{m1}}{20} \frac{1}{C} \frac{1k/315}{1 + 1k/315} \\ &= \frac{g_{m1}}{20} \frac{1}{C} 0.76 \end{aligned}$$

set $W_1 = 200\mu$

$$\begin{aligned} I_{D1} &= \frac{60\mu}{2} \frac{200\mu}{10\mu} (0.2)^2 \\ &= \frac{\mu_n C_{ox}}{2} \frac{W}{L} (V_{GS1} - V_{t1})^2 \\ &= 24\mu A \end{aligned}$$

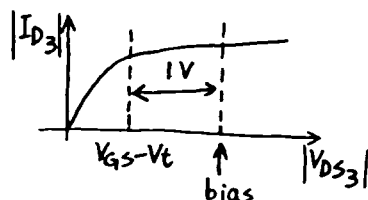
9-31

$$g_{m1} = 240 \mu A/V$$

↓ capacitance

want min W_3 , but must allow

$$\Delta V_{DS3} = 1V \text{ for } \Delta V_o = +1V$$



$$2.5V = |V_{DS3}| = 1 + |V_{GS3} - V_{t3}|$$

$$1.5V = |V_{GS3} - V_{t3}|$$

$$I_{D3} = \frac{\mu_p C_{ox}}{2} \frac{W}{L} (V_{GS} - V_{t})^2$$

$$24\mu = \frac{30\mu}{2} \frac{W}{10\mu} 1.5^2$$

$$7\mu = W_3$$

set $I_1 = 24\mu A$

$$\left(\frac{W}{L}\right)_3 = \left(\frac{W}{L}\right)_4 = \frac{7\mu}{10\mu}$$

$$\left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2 = \frac{200\mu}{10\mu}$$

$$\left(\frac{W}{L}\right)_5 = \frac{3\mu}{3\mu}$$

$$\left(\frac{W}{L}\right)_6 = \frac{6\mu}{3\mu}$$

$$\left(\frac{W}{L}\right)_7 = \frac{200\mu}{3\mu}$$

want $I_{D8} = I_{D7} = 1.6 \text{ mA}$

$$\frac{1.6 \text{ mA}}{24\mu A} = \frac{\left(\frac{W}{L}\right)_7}{\left(\frac{W}{L}\right)_5} = \frac{\frac{200\mu}{3\mu}}{\frac{3\mu}{3\mu}}$$

$$\left(\frac{W}{L}\right)_8 = \frac{159\mu}{3\mu}$$

set $R_1 \gg R_L$

$$\frac{R_2 + R_1}{R_2} = 10 = \frac{2.22k + 20k}{2.22k}$$

m_2 dominates C

$$C \approx C_{dg2} + C_{db2} + \frac{C_{gs8}}{1 + g_{m8} R_L}$$

$$C_{jsw} = 0.5 \frac{fF}{\mu} (418 \mu) = 209 fF \quad 9-32$$

$$C_{jo} = 0.08 \frac{fF}{\mu^2} (200 \mu)(9 \mu)$$

$$= 144 fF$$

$$C_{db2} = 144 + 209 = 353 fF$$

$$C_{dgo1} = 0.35 \frac{fF}{\mu} (200 \mu) = 70 f$$

$$C_{gs8} = \frac{2}{3} W L C_{ox}$$

$$= \frac{2}{3} (159)(3) 0.86 f$$

$$= 273 fF$$

$$C \simeq 353 f + 70 f + \frac{273 f}{1 + \frac{1k}{315}}$$

$$= 488 fF$$

$$BW/ = \frac{g_{m1}}{20} \frac{1}{C} 0.76$$

$$= \frac{240 \mu}{20} \frac{1}{488 f} 0.76$$

$$= 18.7 M \frac{rad}{s}$$

$$\downarrow$$

$$3 MHz$$

9-33

CMOS FEEDBACK AMP

```

VDD 1 0 5V
VSS 9 0 -5V
M4 2 2 1 1 PMOS W=7U L=10U
I1 2 3 24UA
M5 3 3 9 9 NMOS W=3U L=3U
M6 6 3 9 9 NMOS W=6U L=3U
M1 1 4 6 9 NMOS2 W=200U L=10U
M2 5 7 6 9 NMOS2 W=200U L=10U
M3 5 2 1 1 PMOS W=7U L=10U
M8 1 5 8 9 NMOS W=150U L=3U
M7 8 3 9 9 NMOS2 W=200U L=3U
RLOAD 8 0 1K
R1 8 7 20K
R2 7 0 2.22K
VI 4 0 0V AC
.TF V(8) VI
.DC VI -0.4V 0.8V 0.1V
.PLOT DC V(8)
.AC DEC 10 100K 10MEG
.PLOT AC VDB(8)
.MODEL NMOS2 NMOS KP=60U VTO=0.8 LAMBDA=0.02 TOX=400E-10
+ CGSO=350PF CGDO=350PF CRD=353FF CBS=353FF
.MODEL NMOS NMOS KP=60U VTO=0.8 LAMBDA=0.02 TOX=400E-10
+ CGSO=350PF CGDO=350PF
.MODEL PMOS PMOS KP=30U VTO=-0.8 LAMBDA=0.02 TOX=400E-10
+ CGSO=350PF CGDO=350PF
.OPTIONS NOPAGE NOMOD
.OPTIONS VNTOL=1W ABSTOL=1F RELTOL=1U
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** DC TRANSFER CURVES THOM= 27.000 TEMP= 27.000

VOLT	V(8)					
(A)	-2.000E+00	0.	2.000E+00	4.000E+00	6.000E+00	
-4.000E-01	-1.58E+00	+	+	+	+	+
-3.000E-01	-1.58E+00	+	+	+	+	+
-2.000E-01	-1.58E+00	+	+	+	+	+
-1.000E-01	-9.20E-01	+	+	+	+	+
0.	6.61E-01	+	+	+	+	+
1.000E-01	9.39E-01	+	+	+	+	+
2.000E-01	1.71E+00	+	+	+	+	+
3.000E-01	2.11E+00	+	+	+	+	+
4.000E-01	2.38E+00	+	+	+	+	+
5.000E-01	2.55E+00	+	+	+	+	+
6.000E-01	2.58E+00	+	+	+	+	+
7.000E-01	2.58E+00	+	+	+	+	+
8.000E-01	2.58E+00	+	+	+	+	+

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

+0:1	= 5.000E+00	0:2	= 2.721E+00	0:3	= -3.320E+00
+0:4	= 0.	0:5	= 1.795E+00	0:6	= -9.957E-01
+0:7	= 6.601E-04	0:8	= 6.606E-03	0:9	= -5.000E+00

**** MOSFETS

ELEMENT	0:M4	0:M5	0:M6	0:M1	0:M2	0:M3
MODEL	0:PMOS	0:NMOS	0:NMOS	0:NMOS2	0:NMOS2	0:PMOS
ID	-2.400E-05	2.400E-05	5.016E-05	2.573E-05	2.443E-05	-2.443E-05
IBS	0.	0.	0.	-4.004E-14	-4.004E-14	0.
IBD	2.279E-14	-1.680E-14	-4.004E-14	-1.000E-13	-6.795E-14	3.205E-14
VGS	-2.278E+00	1.679E+00	1.679E+00	9.957E-01	9.964E-01	-2.278E+00
VDS	-2.278E+00	1.679E+00	4.004E+00	5.995E+00	2.791E+00	-3.204E+00
VBS	0.	0.	0.	-4.004E+00	-4.004E+00	0.
VTH	-8.000E-01	8.000E-01	8.000E-01	8.000E-01	8.000E-01	-8.000E-01
VDSAT	-1.478E+00	8.798E-01	8.798E-01	1.957E-01	1.964E-01	-1.478E+00
BETA	2.196E-05	6.202E-05	1.296E-04	1.344E-03	1.267E-03	2.235E-05
GAM EFF	0.	0.	0.	0.	0.	0.
GM	3.246E-05	5.456E-05	1.140E-04	2.630E-04	2.488E-04	3.304E-05
GDS	4.591E-07	4.644E-07	9.288E-07	4.596E-07	4.627E-07	4.591E-07
GMB	0.	0.	0.	0.	0.	0.
CDTOT	2.634E-15	1.067E-15	2.183E-15	1.799E-13	1.910E-13	2.708E-15
CGTOT	4.588E-14	7.423E-15	1.489E-14	1.451E-12	1.443E-12	4.596E-14
CSTOT	4.274E-14	6.230E-15	1.246E-14	1.365E-12	1.365E-12	4.274E-14
CBTOT	5.123E-16	1.260E-16	2.519E-16	3.865E-13	4.045E-13	5.123E-16
CGS	4.274E-14	6.230E-15	1.246E-14	1.221E-12	1.221E-12	4.274E-14
CGD	2.634E-15	1.067E-15	2.183E-15	8.380E-14	7.643E-14	2.708E-15

ELEMENT	0:M8	0:M7
MODEL	0:NMOS	0:NMOS2
ID	1.710E-03	1.703E-03
IBS	-5.007E-14	0.
IBD	-1.000E-13	-5.007E-14
VGS	1.788E+00	1.679E+00
VDS	4.993E+00	5.006E+00
VBS	-5.006E+00	0.
VTH	8.000E-01	8.000E-01
VDSAT	9.888E-01	8.798E-01
BETA	3.498E-03	4.401E-03
GAM EFF	0.	0.
GM	3.458E-03	3.871E-03
GDS	3.109E-05	3.096E-05

GMB	0.	0.
CDTOT	5.839E-14	2.045E-13
CGTOT	3.944E-13	4.972E-13
CSTOT	3.302E-13	7.683E-13
CBTOT	5.789E-15	4.924E-13
CGS	3.302E-13	4.153E-13
CGD	5.839E-14	7.346E-14

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(8)/VI	= 9.305E+00
INPUT RESISTANCE AT VI	= 9.999E+19
OUTPUT RESISTANCE AT V(8)	= 1.470E+01

***** AC ANALYSIS THOM= 27.000 TEMP= 27.000

FREQ	VDB(8)					
(A)	5.000E+00	1.000E+01	1.500E+01	2.000E+01	2.500E+01	
1.000E+05	1.93E+01	+	+	+	+	+
1.258E+05	1.93E+01	+	+	+	+	+
1.584E+05	1.93E+01	+	+	+	+	+
1.995E+05	1.93E+01	+	+	+	+	+
2.511E+05	1.93E+01	+	+	+	+	+
3.162E+05	1.93E+01	+	+	+	+	+
3.981E+05	1.93E+01	+	+	+	+	+
5.011E+05	1.93E+01	+	+	+	+	+
6.309E+05	1.92E+01	+	+	+	+	+
7.943E+05	1.92E+01	+	+	+	+	+
1.000E+06	1.91E+01	+	+	+	+	+
1.258E+06	1.89E+01	+	+	+	+	+
1.584E+06	1.87E+01	+	+	+	+	+
1.995E+06	1.84E+01	+	+	+	+	+
2.511E+06	1.79E+01	+	+	+	+	+
3.162E+06	1.73E+01	+	+	+	+	+
3.981E+06	1.64E+01	+	+	+	+	+
5.011E+06	1.53E+01	+	+	+	+	+
6.309E+06	1.40E+01	+	+	+	+	+
7.943E+06	1.26E+01	+	+	+	+	+
1.000E+07	1.09E+01	+	+	+	+	+

9.30

Assume the zero has been eliminated and $|P_3| \gg |P_2| \gg |P_1|$, at the op-amp unity-gain frequency, $|P_1|$ contributes -90° phase shift. If $|P_2|$ contributes -30° phase shift, the phase margin is 60° .
phase shift due to $|P_2| =$

$$-\tan^{-1} \frac{\omega_{\text{unity}}}{|P_2|} = -30^\circ \text{ at } \omega_{\text{unity}}$$

$$\omega_{\text{unity}} = \tan 30^\circ \cdot |P_2| = \frac{\sqrt{3}}{3} |P_2|$$

$$= a_0 |P_1|$$

$$a_0 |P_1| = \frac{\sqrt{3}}{3} |P_2|$$

$$g_{m1} R_1 g_{m6} R_2 \frac{1}{g_{m6} R_2 R_1 C} = \frac{\sqrt{3}}{3} \frac{g_{m6}}{C_1 + C_2}$$

$$\frac{g_{m1}}{C} = \frac{\sqrt{3}}{3} \frac{g_{m6}}{C_1 + C_2}$$

From the example in Section 9.4.3,

$$g_{m1} = 1 \text{ mA/V}, g_{m6} = 1.55 \text{ mA/V}, C_1 + C_2 \approx 5 \text{ pF}$$

$$C = \sqrt{3} \frac{g_{m1}}{g_{m6}} (C_1 + C_2) = 1.7 \frac{1}{1.55} 5 = 5.4 \text{ pF}$$

9.31

(a) Similar to Problem 9.30, the op-amp unity-gain frequency

$$\omega_{\text{unity}} = 2 \cdot \tan 45^\circ |P_2| = 2 |P_2| = a_0 |P_1|$$

$$\frac{g_{m1}}{C} = 2 \frac{g_{m6}}{C_1 + C_2}$$

$$\frac{0.5}{C} = 2 \frac{2}{0.1 + 8}$$

$$C = 1 \text{ pF}$$

$$(b) R_2 = \frac{1}{g_{m6}} = 500 \Omega$$

9.32

Similar to Problem 9.31a,

$$|P_2| = \frac{g_{m6}}{C + C_2} \frac{C}{C_1}$$

$$a_0 |P_1| = 2 |P_2|$$

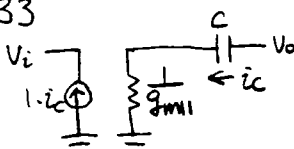
$$\frac{g_{m1}}{C} = 2 \frac{g_{m6}}{C + C_2} \frac{C}{C_1}$$

$$\frac{0.5}{C} = 2 \frac{2}{C + 8} \frac{C}{0.1}$$

$$C = 0.32 \text{ pF}$$

It is smaller than the compensation capacitor in Problem 9.31a.

9.33



$$i_C = \frac{V_o}{\frac{1}{g_{m11}} + \frac{1}{sC}} = \frac{s g_{m11} C}{g_{m11} + sC} V_o$$

In (9.40a), (9.40b) and (9.41), C_1 can be ignored and sC replaced by $\frac{s g_{m11} C}{g_{m11} + sC}$;

$$\frac{V_o}{i_s} = \frac{g_{m6} R_1 R_2}{1 + s R_2 C_2 + s(1 + g_{m6} R_1) R_2 C} \text{ becomes}$$

$$\frac{V_o}{i_s} = \frac{g_{m6} R_1 R_2}{1 + s R_2 C_2 + s(1 + g_{m6} R_1) R_2 C \frac{g_{m11}}{g_{m11} + sC}}$$

$$= \frac{g_{m6} R_1 R_2 (g_{m11} + sC)}{g_{m11} + s[C + g_{m11} R_2 C_2 + (1 + g_{m6} R_1) g_{m11} R_2 C] + s^2 R_2 C C}$$

There is a zero at $-\frac{g_{m11}}{C}$

9-35

9.34

The denominator of (9.27) is

$$1 + S(C_2 R_2 + C_1 R_1) + S^2 R_2 R_1 C_2 C_1 + C[S(R_2 + R_1 + g_m R_2 R_1) + S^2 R_2 R_1 (C_2 + C_1)] = 0$$

$$1 + C \frac{S(R_2 + R_1 + g_m R_2 R_1) + S^2 R_2 R_1 (C_2 + C_1)}{1 + S(C_2 R_2 + C_1 R_1) + S^2 R_2 R_1 C_2 C_1} = 0$$

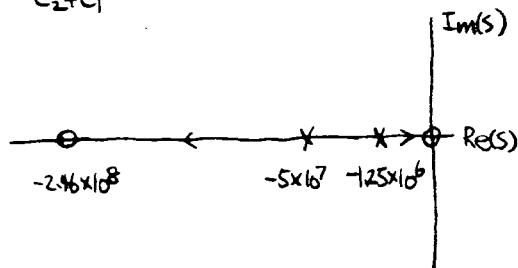
Roots of the denominator:

$$-\frac{1}{R_2 C_2} = -1.25 \times 10^6 \text{ rad/s}$$

$$-\frac{1}{R_1 C_1} = -5 \times 10^7 \text{ rad/s}$$

Roots of the numerator:

$$D, -\frac{g_m}{C_2 + C_1} = -2.46 \times 10^8 \text{ rad/s}$$



9.35

$$P_1 \approx -\frac{1}{g_{m1} R_1 g_{m2} R_2 R_0 C_{m2}}$$

$$P_2 \approx -\frac{g_{m1}}{C_{m1}}$$

$$P_3 \approx -\frac{g_{m2}}{C_2}$$

$$A_0 = g_{m0} R_0 g_{m1} R_1 g_{m2} R_2$$

$$A_0 |P_1| = 1 \cdot |P_2|$$

$$\therefore C_{m2} = \frac{g_{m0}}{g_{m1}} C_{m1} = C_{m1}$$

 $C_{m1}, C_{m2} \geq C_0, C_1, C_2$ should be satisfied.One possible answer is $C_{m1} = C_{m2} = 10 \text{ pF}$

$$|P_3| = \frac{6g_{m1}}{6 \text{ pF}} \gg |P_2| = \frac{g_{m1}}{10 \text{ pF}} \gg |P_1| = \frac{|P_2|}{A_0}$$

9.36

Assume $|P_2| \gg |P_1|$. At ω_{unity} , P_1 contributes -90° phase shift. If P_2 contributes -30° , the phase margin will be 60° .

$$-\tan^{-1} \frac{\omega_{\text{unity}}}{|P_2|} = -30^\circ$$

$$\omega_{\text{unity}} = \frac{\sqrt{3}}{3} |P_2|$$

$$A_0 \cdot |P_1| = 1 \cdot \omega_{\text{unity}} = 1 \cdot \frac{\sqrt{3}}{3} |P_2|$$

$$P_1 \approx -\frac{1}{g_{m1} R_1 g_{m2} R_2 R_0 C_{m2}}$$

$$P_2 \approx -\frac{g_{m1}}{C_{m1}}$$

$$A_0 = g_{m0} R_0 g_{m1} R_1 g_{m2} R_2$$

$$\therefore C_{m2} = \sqrt{3} C_{m1}$$

One possible answer is $C_{m1} = 10 \text{ pF}$,

$$C_{m2} = 17 \text{ pF}.$$

9.37

$$|P_1| = \frac{1}{R_0 C_L}$$

 $A_0, |P_2|$ are constant.To give a 45° phase margin,

$$A_0 \cdot |P_1| = 1 \cdot \tan(90^\circ - 45^\circ) |P_2| = 1 \cdot |P_2|$$

$$C_L = \frac{A_0}{|P_2| R_0}$$

To give a 60° phase margin,

$$A_0 \cdot |P_1| = 1 \cdot \tan(90^\circ - 60^\circ) |P_2| = 1 \cdot \frac{\sqrt{3}}{3} |P_2|$$

$$C'_L = \sqrt{3} \frac{A_0}{|P_2| R_0} = \sqrt{3} C_L = 3.4 \text{ pF}$$

9.38

$$(a) a_0 \cdot \frac{1}{R_0 C_L} = |P_2|$$

$$g_{m1} R_0 \frac{1}{R_0 C_L} = \frac{g_{m1}}{C_L} = |P_2|$$

$$\frac{0.3 \times 10^{-3}}{C_L} = 200 \times 10^6$$

$$C_L = 1.5 \times 10^{-12} \text{ F} = 1.5 \text{ pF}$$

$$(b) SR = \frac{I_{TACL}}{C_L} = \frac{0.5 \text{ mA}}{1.5 \text{ pF}}$$

$$= 330 \text{ V}/\mu\text{s}$$

9.39

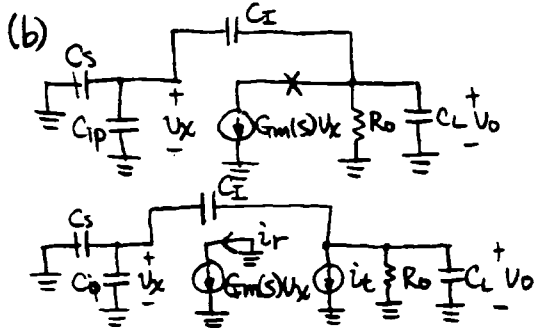
(a) The equivalent load is

$$C'_L = C_L + C_{L1} \parallel (C_S + C_{ip})$$

$$= 1.5 + 4 \parallel (0.4 + 0.1)$$

$$= 1.9 \text{ pF}$$

$$SR = \frac{0.2 \text{ mA}}{1.9 \text{ pF}} = 105 \text{ V}/\mu\text{s}$$



$$f = \frac{v_x}{v_o} = \frac{C_I}{C_I + (C_S + C_{ip})} = \frac{4}{4 + (0.4 + 0.1)}$$

$$= 0.89$$

$$G_m(s) = \frac{g_{m1}}{1 - s/P_2}$$

$$R = -\frac{i_r}{i_t} = -\left[-i_t \frac{1}{V_{R_0 + sC'_L}} f G_m(s) \right] / i_t$$

$$= \frac{G_m(s) R_0 f}{1 + s R_0 C'_L} = \frac{g_{m1} R_0 f}{(1 + s R_0 C'_L)(1 - s/P_2)}$$

To locate ω_{unity} , $\omega_{unity} \gg |P_1| = \frac{1}{R_0 C'_L}$ and

$$|R| \approx \frac{g_{m1} R_0 f}{|s R_0 C'_L (1 - s/P_2)|}$$

$$= \frac{g_{m1} f}{C'_L |s| |1 - s/P_2|}$$

$$= \frac{0.1 \times 10^{-3} \times 0.89}{1.9 \times 10^{-12} |j\omega| |1 - j\omega/P_2|}$$

$$= \frac{4.7 \times 10^7}{\omega \sqrt{1 + \omega^2/P_2^2}}$$

$$= 1$$

$$\omega_{unity} = 4.7 \times 10^7 \text{ rad/s} \ll |P_2|$$

The phase shift from P_1 is 90° .

The phase shift from P_2 is

$$\tan^{-1}\left(\frac{\omega_{unity}}{|P_2|}\right) = \tan^{-1}\left(\frac{4.7 \times 10^7}{2 \times 10^8}\right) = 13^\circ$$

The phase margin is

$$180^\circ - (90^\circ + 13^\circ) = 77^\circ$$

9.40

$$v_x = -\frac{Z_1}{Z_1 + Z_2} v_t$$

$$v_r = a_v v_x$$

$$R = -\frac{v_r}{v_t} = a_v \frac{Z_1}{Z_1 + Z_2}$$

There are 4 possibilities:

(1) $R = a_v \frac{R_1}{R_1 + R_2}$, and the phase shift is 0° ;

(2) $R = a_v \frac{R_1}{R_1 + 1/j\omega C_2} = a_v \frac{j\omega R_1 C_2}{1 + j\omega R_1 C_2}$, and the phase shift is between 0° and 90° ;

(3) $R = a_v \frac{1/j\omega C_1}{1/j\omega C_1 + R_2} = a_v \frac{1}{1 + j\omega R_2 C_1}$, and the phase shift is between -90° and 0° ;

(4) $R = a_v \frac{1/j\omega C_1}{1/j\omega C_1 + 1/j\omega C_2} = a_v \frac{C_2}{C_1 + C_2}$, and the phase shift is 0° .

The phase shift never reaches -180° , so the circuit is stable.

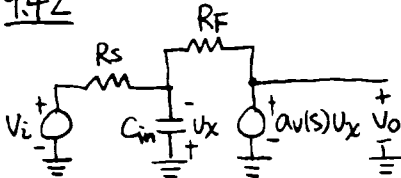
9.41

$$R = a_v(s) \frac{j\omega RC}{1+j\omega RC}$$

$$= \frac{a_v}{(1 + \frac{j\omega}{|P_1|})(1 + \frac{j\omega}{|P_2|})} \frac{j\omega RC}{1+j\omega RC}$$

The $a_v \cdot j\omega RC$ term contributes a 90° phase shift. Each of the 3 LHP poles contributes a -90° phase shift when $\omega \rightarrow \infty$. The total phase shift never reaches -180° for $0 < \omega < \infty$, so the circuit is stable.

9.42



$$R = \frac{R_s \parallel \frac{1}{sC_{in}}}{R_F + R_s \parallel \frac{1}{sC_{in}}} a_v(s)$$

$$= \frac{\frac{R_s}{1 + s(R_s \parallel R_F)C_{in}}}{1 + s(R_s \parallel R_F)C_{in}} \frac{1000}{(1 + \frac{s}{100})(1 + \frac{s}{10^6})}$$

$$= \frac{\frac{1}{2}}{1 + s \cdot 50k \cdot C_{in}} \frac{1000}{(1 + \frac{s}{100})(1 + \frac{s}{10^6})}$$

$$= \frac{500}{(1 + s \cdot 50k \cdot C_{in})(1 + \frac{s}{100})(1 + \frac{s}{10^6})}$$

(a) $C_{in} = 0$

$$R = \frac{500}{(1 + \frac{s}{100})(1 + \frac{s}{10^6})}$$

When $s = j\omega = j5 \times 10^4$, $|R(j\omega)| = 1$.

When $s = j\omega = j10^5$, $|a_v(j\omega)| = 1$.

The latter frequency is twice the former.

(b)

C_{in} (PF)	ω_u (rad/s)	poles (rad/s)	phase shift	phase margin
0	5×10^4	100	-90°	87°
		10^6	-3°	
4		100	-90°	86°
		10^6	-3°	
		5×10^6	-1°	
20		100	-90°	84°
		10^6 (double)	-6°	

Even with the addition of the third pole from C_{in} , the phase shift never reaches -180° at ω_u .

9.43

(a) See next page.
(b) The unity-gain frequency is $\sim 4 \text{ MHz}$.

The phase margin is $\sim 70^\circ$.

The gain margin is $\sim 10 \text{ dB}$.

```

RETURN RATIO
VDD 1 0 5
VSS 2 0 -5
.GLOBAL 1 2
.SUBCKT AMP (6 5 9)
  IRLAS 3 2 200
  M1 7 5 4 4 CHOSP W=100U L=6.4U
  M2 8 6 4 4 CHOSP W=100U L=6.4U
  M3 7 7 2 2 CHOSP W=50U L=6.4U
  M4 8 7 2 2 CHOSP W=50U L=6.4U
  M5 4 3 1 1 CHOSP W=100U L=6.4U
  M6 9 8 2 2 CHOSP W=100U L=6.4U
  M7 9 3 1 1 CHOSP W=100U L=6.4U
  M8 3 3 1 1 CHOSP W=100U L=6.4U
  M9 10 1 8 2 CHOSP W=6.1U L=6.4U
  CCOMP 10 9 5P
  .MODEL CHOSP PHOS LEVEL=1 LAMBDA=0.0313 VTO=0.7 KP=60.4U LD=0.12U
  .MODEL CHOSP PHOS LEVEL=1 LAMBDA=0.0156 VTO=-0.7 KP=30.2U LD=0.18U
.ENDS AMP
.OPTIONS NOMOD
XKRV (0 11 12) AMP
VT 11 12 AC 1
R1 12 0 1G
XKRI (0 21 22) AMP
IT 0 31 AC 1
VDUMY1 31 21 0
VDUMY2 22 31 0
R2 31 0 1G
.AC DEC 5 1 1G
.PRINT AC XKRV=PAR('VM(12)/VM(11)*COS(3.14*(VP(12)-VP(11))/180)')\
XKRI=PAR('VM(12)/VM(11)*SIN(3.14*(VP(12)-VP(11))/180)')\
XKRII=PAR('IM(VDUMY2)/IM(VDUMY1)*COS(3.14*(IP(VDUMY2)-IP(VDUMY1))/180)')\
XKRII=PAR('IM(VDUMY2)/IM(VDUMY1)*SIN(3.14*(IP(VDUMY2)-IP(VDUMY1))/180)')
.OPTIONS SUPC
.WIDTH OUT=80
.END
***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000
+0:1 = 5.000E+00 0:2 = -5.000E+00 0:11 = -4.599E-05
+0:12 = -4.599E-05 0:21 = -4.599E-05 0:22 = -4.599E-05
+0:31 = -4.599E-05 1:3 = 4.019E+00 1:4 = 8.972E-01
+1:7 = -4.096E+00 1:8 = -4.106E+00 1:10 = -4.106E+00
+2:3 = 4.019E+00 2:4 = 8.972E-01 2:7 = -4.096E+00
+2:8 = -4.106E+00 2:10 = -4.106E+00
**** MOSFETS
SUBCKT XKRV
ELEMENT 1:M1 1:M2 1:M3 1:M4 1:M5 1:M6
MODEL 1:CHOSP 1:CHOSP 1:CHOSP 1:CHOSP 1:CHOSP 1:CHOSP
ID -1.048E-05 -1.048E-05 1.048E-05 1.048E-05 -2.096E-05 2.124E-05
IAS 0. 0. 0. 0. 0. 0.
IRD 4.993E-14 5.004E-14 -9.039E-15 -8.935E-15 4.103E-14 -5.000E-14
VGS -8.972E-01 -8.972E-01 9.039E-01 9.039E-01 -9.807E-01 8.935E-01
VDS -4.993E+00 -5.003E+00 9.039E-01 8.935E-01 -4.102E+00 5.000E+00
VBS 0. 0. 0. 0. 0. 0.
VTH -7.000E-01 -7.000E-01 7.000E-01 7.000E-01 -7.000E-01 7.000E-01
VDSAT -1.972E-01 -1.972E-01 2.039E-01 2.039E-01 -2.807E-01 1.935E-01
ETA 5.390E-04 5.390E-04 5.041E-04 5.040E-04 5.320E-04 1.134E-03
GAM KFF 0. 0. 0. 0. 0. 0.
GM 1.063E-04 1.063E-04 1.028E-04 1.028E-04 1.493E-04 2.195E-04
GDS 1.517E-07 1.516E-07 3.190E-07 3.190E-07 3.073E-07 5.747E-07
GMB 0. 0. 0. 0. 0. 0.
COTOT 0. 0. 0. 0. 0. 0.
COTOT 0. 0. 0. 0. 0. 0.
COTOT 0. 0. 0. 0. 0. 0.
COTOT 0. 0. 0. 0. 0. 0.
COTOT 0. 0. 0. 0. 0. 0.
CGS 0. 0. 0. 0. 0. 0.
CGD 0. 0. 0. 0. 0. 0.
SUBCKT XKRI
ELEMENT 1:M7 1:M8 1:M9 1:M10 1:M11 1:M12
MODEL 1:CHOSP 1:CHOSP 1:CHOSP 1:CHOSP 1:CHOSP 1:CHOSP
ID -2.124E-05 -2.000E-05 -9.025E-13 -1.048E-05 -1.048E-05 1.048E-05
IAS 0. 0. 0. 0. 0. 0.
IRD 5.000E-14 9.807E-15 -8.935E-15 4.993E-14 5.004E-14 -9.039E-15
VGS -8.907E-01 -9.807E-01 9.106E+00 -8.972E-01 -8.972E-01 9.039E-01
VDS -5.000E+00 -9.807E-01 -1.795E-09 -4.993E+00 -5.003E+00 9.039E-01
VBS 0. 0. 0. 0. 0. 0.
VTH -7.000E-01 -7.000E-01 7.000E-01 -7.000E-01 -7.000E-01 7.000E-01
VDSAT -2.807E-01 -1.972E-01 1.795E-09 -1.972E-01 -1.972E-01 2.039E-01
ETA 5.390E-04 5.076E-04 5.981E-05 5.389E-04 5.390E-04 5.041E-04
GAM KFF 0. 0. 0. 0. 0. 0.
GM 1.513E-04 1.425E-04 1.074E-13 1.063E-04 1.063E-04 1.028E-04
GDS 3.073E-07 3.073E-07 5.028E-04 1.517E-07 1.516E-07 3.190E-07
GMB 0. 0. 0. 0. 0. 0.
COTOT 0. 0. 0. 0. 0. 0.
COTOT 0. 0. 0. 0. 0. 0.
COTOT 0. 0. 0. 0. 0. 0.
COTOT 0. 0. 0. 0. 0. 0.
COTOT 0. 0. 0. 0. 0. 0.
CGS 0. 0. 0. 0. 0. 0.
CGD 0. 0. 0. 0. 0. 0.
SUBCKT XKRII
ELEMENT 2:M4 2:M5 2:M6 2:M7 2:M8 2:M9
MODEL 2:CHOSP 2:CHOSP 2:CHOSP 2:CHOSP 2:CHOSP 2:CHOSP
ID 1.048E-05 -2.096E-05 2.124E-05 -2.124E-05 -2.000E-05 -9.025E-13
IAS 0. 0. 0. 0. 0. -8.935E-15
IRD -8.935E-15 4.103E-14 -5.000E-14 5.000E-14 9.807E-15 -8.935E-15
VGS 9.039E-01 -9.807E-01 8.935E-01 -9.807E-01 -9.807E-01 9.106E+00
VDS 8.935E-01 -4.102E+00 5.000E+00 -5.000E+00 -9.807E-01 -1.795E-09
VBS 0. 0. 0. 0. 0. -8.935E-01
VTH 7.000E-01 -7.000E-01 7.000E-01 -7.000E-01 -7.000E-01 7.000E-01

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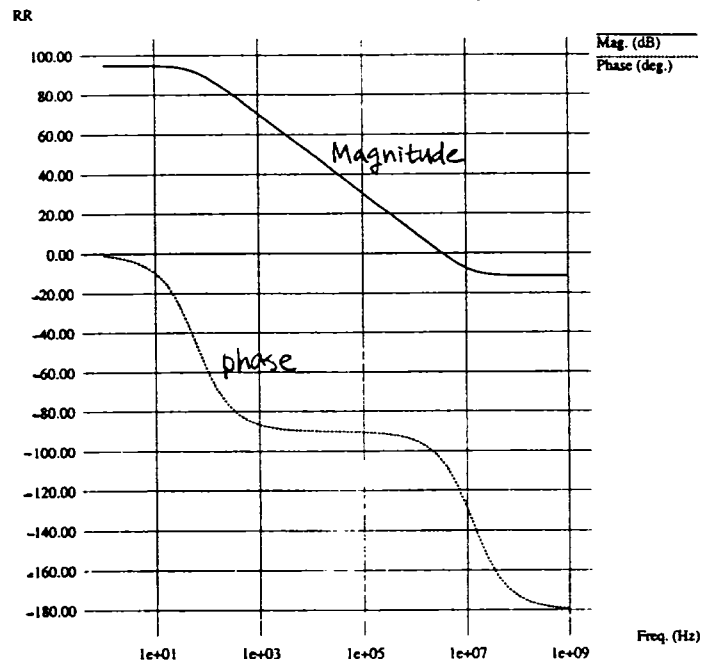
VDSAT 2.059E-01 -2.807E-01 1.935E-01 -2.807E-01 -2.807E-01 1.795E-09
ETA 5.040E-04 5.320E-04 1.134E-03 5.390E-04 5.076E-04 5.981E-05
GAM KFF 0. 0. 0. 0. 0. 0.
GM 1.028E-04 1.493E-04 2.195E-04 1.513E-04 1.425E-04 1.074E-13
GDS 3.190E-07 3.073E-07 5.747E-07 3.073E-07 3.073E-07 5.028E-04
GMB 0. 0. 0. 0. 0. 0.
COTOT 0. 0. 0. 0. 0. 0.
COTOT 0. 0. 0. 0. 0. 0.
COTOT 0. 0. 0. 0. 0. 0.
COTOT 0. 0. 0. 0. 0. 0.
COTOT 0. 0. 0. 0. 0. 0.
CGS 0. 0. 0. 0. 0. 0.
CGD 0. 0. 0. 0. 0. 0.

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***** AC ANALYSIS THOM= 27.000 TEMP= 27.000

FREQ	XKRV	XKRI	XKRII
1.0000E+00	5.601E+04	-1.024E+03	9.999E+27
1.5848E+00	5.598E+04	-1.570E+03	9.999E+27
2.5118E+00	5.592E+04	-2.434E+03	9.999E+27
3.9810E+00	5.577E+04	-3.796E+03	9.999E+27
6.3095E+00	5.540E+04	-5.925E+03	9.999E+27
1.0000E+01	5.449E+04	-9.187E+03	9.999E+27
1.5848E+01	5.233E+04	-1.393E+04	9.999E+27
2.5118E+01	4.761E+04	-2.005E+04	9.999E+27
3.9810E+01	3.881E+04	-2.588E+04	9.999E+27
6.3095E+01	2.651E+04	-2.800E+04	9.999E+27
1.0000E+02	1.475E+04	-2.470E+04	9.999E+27
1.5848E+02	6.977E+03	-1.852E+04	9.999E+27
2.5118E+02	2.999E+03	-1.263E+04	9.999E+27
3.9810E+02	1.231E+03	-8.240E+03	9.999E+27
6.3095E+02	4.951E+02	-5.269E+03	9.999E+27
1.0000E+03	1.970E+02	-3.342E+03	9.999E+27
1.5848E+03	7.783E+01	-2.113E+03	9.999E+27
2.5118E+03	3.045E+01	-1.334E+03	9.999E+27
3.9810E+03	1.171E+01	-8.423E+02	9.999E+27
6.3095E+03	4.347E+00	-5.315E+02	9.999E+27
1.0000E+04	1.469E+00	-3.354E+02	9.999E+27
1.5848E+04	3.600E-01	-2.116E+02	9.999E+27
2.5118E+04	-5.870E-02	-1.335E+02	9.999E+27
3.9810E+04	-2.109E-01	-8.425E+01	9.999E+27
6.3095E+04	-2.624E-01	-5.316E+01	9.999E+27
1.0000E+05	-2.771E-01	-3.354E+01	9.999E+27
1.5848E+05	-2.793E-01	-2.116E+01	9.999E+27
2.5118E+05	-2.779E-01	-1.335E+01	9.999E+27
3.9810E+05	-2.759E-01	-8.425E+00	9.999E+27
6.3095E+05	-2.742E-01	-5.315E+00	9.999E+27
1.0000E+06	-2.729E-01	-3.354E+00	9.999E+27
1.5848E+06	-2.721E-01	-2.116E+00	9.999E+27
2.5118E+06	-2.715E-01	-1.335E+00	9.999E+27
3.9810E+06	-2.711E-01	-8.424E-01	9.999E+27
6.3095E+06	-2.709E-01	-5.315E-01	9.999E+27
1.0000E+07	-2.707E-01	-3.353E-01	9.999E+27
1.5848E+07	-2.707E-01	-2.115E-01	9.999E+27
2.5118E+07	-2.706E-01	-1.335E-01	9.999E+27
3.9810E+07	-2.706E-01	-8.421E-02	9.999E+27
6.3095E+07	-2.706E-01	-5.313E-02	9.999E+27
1.0000E+08	-2.706E-01	-3.353E-02	9.999E+27
1.5848E+08	-2.706E-01	-2.115E-02	9.999E+27
2.5118E+08	-2.706E-01	-1.335E-02	9.999E+27
3.9810E+08	-2.706E-01	-8.421E-03	9.999E+27
6.3095E+08	-2.706E-01	-5.313E-03	9.999E+27
1.0000E+09	-2.706E-01	-3.353E-03	9.999E+27

Return Ratio versus Freq.



9-39

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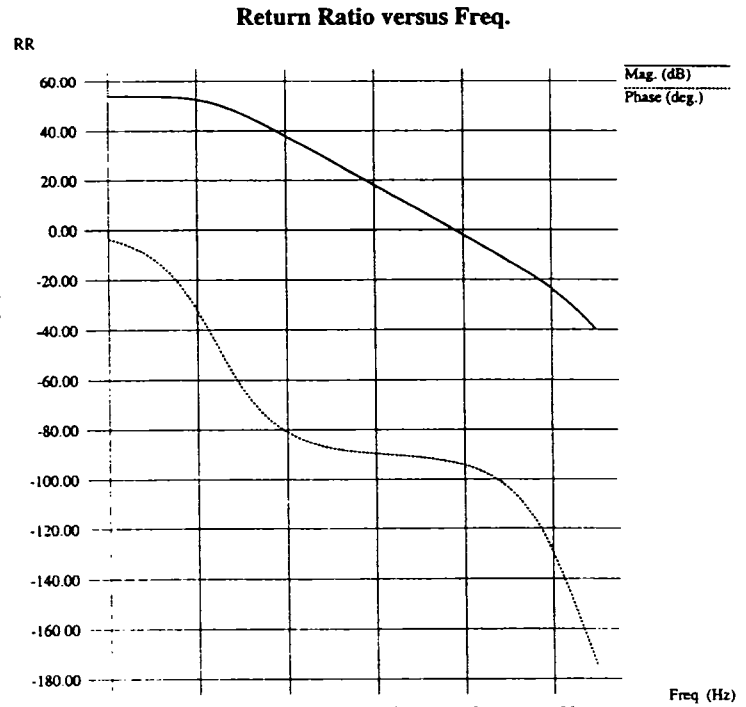
RETURN RATIO
.SUBCKT AMP (1 2)
RAMP 3 0 LAPLACE 0 1 1000 / 1 10.001M 0.01U
R1 1 0 100K
R2 2 3 100K
CIN 1 0 4P
.ENDS AMP
.OPTIONS NOMOD
XKRV (11 12) AMP
VT 12 11 AC 1

XKVI (21 22) AMP
IT 0 31 AC 1
VDUMY1 31 21 0
VDUMY2 22 31 0

.AC DEC 10 1 300K
.PRINT AC KRVV=PAR('VM(12)/VM(11)*COS(3.14*(VP(12)-VP(11))/180)')\
KRVV=PAR('VM(12)/VM(11)*SIN(3.14*(VP(12)-VP(11))/180)')\
RRIR=PAR('IM(VDUMY2)/IM(VDUMY1)*COS(3.14*(IP(VDUMY2)-IP(VDUMY1))/180)')\
RRII=PAR('IM(VDUMY2)/IM(VDUMY1)*SIN(3.14*(IP(VDUMY2)-IP(VDUMY1))/180)')\
.OPTIONS SPICE
.WIDTH OUT=80
.END

```

***** AC ANALYSIS					TNO= 27.000 TEMP= 27.000	
FREQ	KRVV	KRVV	RRIR	RRII		
1.0000E+00	9.969E+02	-6.414E+01	9.969E+02	-6.415E+01		
1.2589E+00	9.946E+02	-8.016E+01	9.946E+02	-8.016E+01		
1.5848E+00	9.910E+02	-1.001E+02	9.910E+02	-1.001E+02		
1.9952E+00	9.853E+02	-1.249E+02	9.853E+02	-1.249E+02		
2.5118E+00	9.764E+02	-1.554E+02	9.764E+02	-1.554E+02		
3.1622E+00	9.627E+02	-1.926E+02	9.627E+02	-1.926E+02		
3.9810E+00	9.417E+02	-2.368E+02	9.417E+02	-2.368E+02		
5.0118E+00	9.103E+02	-2.878E+02	9.103E+02	-2.878E+02		
6.3095E+00	8.646E+02	-3.438E+02	8.646E+02	-3.438E+02		
7.9432E+00	8.010E+02	-4.006E+02	8.010E+02	-4.007E+02		
1.0000E+01	7.173E+02	-4.514E+02	7.173E+02	-4.514E+02		
1.2589E+01	6.154E+02	-4.873E+02	6.154E+02	-4.874E+02		
1.5848E+01	5.024E+02	-5.006E+02	5.024E+02	-5.006E+02		
1.9952E+01	3.892E+02	-4.879E+02	3.892E+02	-4.880E+02		
2.5118E+01	2.869E+02	-4.524E+02	2.868E+02	-4.524E+02		
3.1622E+01	2.026E+02	-4.018E+02	2.025E+02	-4.018E+02		
3.9810E+01	1.383E+02	-3.448E+02	1.383E+02	-3.448E+02		
5.0118E+01	9.223E+01	-2.885E+02	9.220E+01	-2.885E+02		
6.3095E+01	6.050E+01	-2.372E+02	6.047E+01	-2.372E+02		
7.9432E+01	3.932E+01	-1.926E+02	3.928E+01	-1.926E+02		
1.0000E+02	2.547E+01	-1.552E+02	2.543E+01	-1.552E+02		
1.2589E+02	1.652E+01	-1.244E+02	1.648E+01	-1.244E+02		
1.5848E+02	1.080E+01	-9.943E+01	1.076E+01	-9.944E+01		
1.9952E+02	7.156E+00	-7.927E+01	7.116E+00	-7.928E+01		
2.5118E+02	4.846E+00	-6.311E+01	4.806E+00	-6.312E+01		
3.1622E+02	3.385E+00	-5.020E+01	3.345E+00	-5.021E+01		
3.9810E+02	2.462E+00	-3.991E+01	2.422E+00	-3.992E+01		
5.0118E+02	1.881E+00	-3.172E+01	1.841E+00	-3.173E+01		
6.3095E+02	1.515E+00	-2.521E+01	1.475E+00	-2.522E+01		
7.9432E+02	1.284E+00	-2.002E+01	1.244E+00	-2.003E+01		
1.0000E+03	1.140E+00	-1.591E+01	1.100E+00	-1.591E+01		
1.2589E+03	1.049E+00	-1.263E+01	1.009E+00	-1.264E+01		
1.5848E+03	9.923E-01	-1.003E+01	9.523E-01	-1.004E+01		
1.9952E+03	9.568E-01	-7.971E+00	9.168E-01	-7.981E+00		
2.5118E+03	9.347E-01	-6.329E+00	8.946E-01	-6.341E+00		
3.1622E+03	9.209E-01	-5.024E+00	8.809E-01	-5.039E+00		
3.9810E+03	9.124E-01	-3.986E+00	8.723E-01	-4.005E+00		
5.0118E+03	9.072E-01	-3.161E+00	8.671E-01	-3.184E+00		
6.3095E+03	9.041E-01	-2.503E+00	8.639E-01	-2.533E+00		
7.9432E+03	9.022E-01	-1.979E+00	8.620E-01	-2.017E+00		
1.0000E+04	9.013E-01	-1.561E+00	8.608E-01	-1.608E+00		
1.2589E+04	9.008E-01	-1.225E+00	8.602E-01	-1.284E+00		
1.5848E+04	9.009E-01	-9.557E-01	8.598E-01	-1.029E+00		
1.9952E+04	9.013E-01	-7.364E-01	8.596E-01	-8.296E-01		
2.5118E+04	9.021E-01	-5.563E-01	8.595E-01	-6.737E-01		
3.1622E+04	9.035E-01	-4.060E-01	8.594E-01	-5.537E-01		
3.9810E+04	9.056E-01	-2.775E-01	8.592E-01	-4.635E-01		
5.0118E+04	9.089E-01	-1.643E-01	8.585E-01	-3.983E-01		
6.3095E+04	9.135E-01	-6.085E-02	8.570E-01	-3.552E-01		
7.9432E+04	9.199E-01	4.066E-02	8.534E-01	-3.321E-01		
1.0000E+05	9.281E-01	1.386E-01	8.457E-01	-3.280E-01		
1.2589E+05	9.381E-01	2.400E-01	8.302E-01	-3.418E-01		
1.5848E+05	9.493E-01	3.492E-01	8.019E-01	-3.711E-01		
1.9952E+05	9.605E-01	4.718E-01	7.550E-01	-4.109E-01		
2.5118E+05	9.706E-01	6.144E-01	6.858E-01	-4.523E-01		
3.1622E+05	9.788E-01	7.858E-01	5.949E-01	-4.842E-01		



9.44 (a) See above.
 (b) The unity-gain frequency is ~ 8 kHz.
 The phase margin is $\sim 90^\circ$.
 The gain margin is ~ 40 dB.


```

RETURN RATIO
.SUBCKT AMP (3 4)
VDD 1 0 5
IB 1 2 0.5M
NL 2 3 0 0 CMOSEN W=50U L=0.6U
R1 2 4 20K
C1 2 0 2P
.MODEL CMOSEN NMOS LEVEL=1 LAMBDA=0.0333 VTO=0.6 KP=194U
.ENDS AMP
.OPTIONS NOMOD
XKRV (11 12) AMP
VT 11 12 AC 1

XKRI (21 22) AMP
IT 0 31 AC 1
VDUMMY1 31 21 0
VDUMMY2 22 31 0

.AC DEC 5 1 1G
.PRINT AC RKVR=PAR('VM(12)/VM(11)*COS(3.14*(VP(12)-VP(11))/180)')\
RKVI=PAR('VM(12)/VM(11)*SIN(3.14*(VP(12)-VP(11))/180)')\
RKIR=PAR('IN(VDUMMY2)/IN(VDUMMY1)*COS(3.14*(IP(VDUMMY2)-IP(VDUMMY1))/180)')\
RKII=PAR('IN(VDUMMY2)/IN(VDUMMY1)*SIN(3.14*(IP(VDUMMY2)-IP(VDUMMY1))/180)')\
.OPTIONS SPICE
.WIDTH OUT=80
.END

```

3.9810E+07	2.569E-01	-8.141E+00	9.999E+27	-1.592E+25
6.3095E+07	1.008E-01	-5.139E+00	9.999E+27	1.592E+25
1.0000E+08	3.920E-02	-3.243E+00	9.999E+27	-1.592E+25
1.5848E+08	1.501E-02	-2.046E+00	9.999E+27	-1.592E+25
2.5118E+08	5.594E-03	-1.291E+00	9.999E+27	1.592E+25
3.9810E+08	1.988E-03	-8.149E-01	9.999E+27	-1.592E+25
6.3095E+08	6.402E-04	-5.142E-01	9.999E+27	1.592E+25
1.0000E+09	1.596E-04	-3.244E-01	9.999E+27	-1.592E+25

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

+0:11	= 8.453E-01 0:12	= 8.453E-01 0:21	= 8.453E-01
+0:22	= 8.453E-01 0:31	= 8.453E-01 1:1	= 5.000E+00
+1:2	= 8.453E-01 2:1	= 5.000E+00 2:2	= 8.453E-01

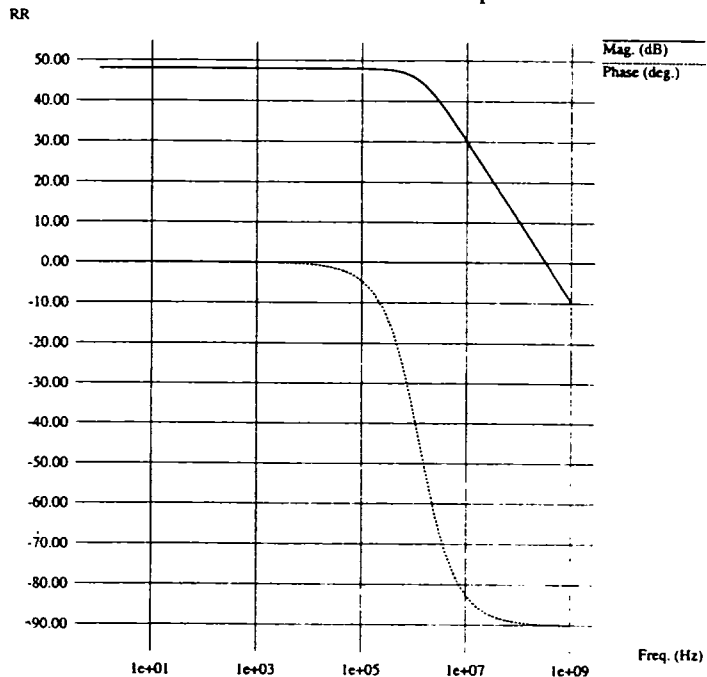
**** MOSFETS

SUBCKT	XKRV	XKRI
ELEMENT	1:NL	2:NL
MODEL	1:CMOSEN	2:CMOSEN
ID	5.000E-04	5.000E-04
IBS	0.	0.
IBD	-8.453E-15	-8.453E-15
VGS	8.453E-01	8.453E-01
VDS	8.453E-01	8.453E-01
VBS	0.	0.
VTH	6.000E-01	6.000E-01
VDSAT	2.453E-01	2.453E-01
BETA	1.662E-02	1.662E-02
GAM KFF	0.	0.
GM	4.077E-03	4.077E-03
GDS	1.619E-05	1.619E-05
GMS	0.	0.
COTOT	0.	0.
COTOT	0.	0.
CSTOT	0.	0.
CSTOT	0.	0.
CGS	0.	0.
CGD	0.	0.

***** AC ANALYSIS THOM= 27.000 TEMP= 27.000

FREQ	RKVR	RKVI	RKIR	RKII
1.0000E+00	2.517E+02	-4.011E-01	9.999E+27	1.592E+25
1.5848E+00	2.517E+02	-4.012E-01	9.999E+27	1.592E+25
2.5118E+00	2.517E+02	-4.014E-01	9.999E+27	1.592E+25
3.9810E+00	2.517E+02	-4.017E-01	9.999E+27	1.592E+25
6.3095E+00	2.517E+02	-4.022E-01	9.999E+27	1.592E+25
1.0000E+01	2.517E+02	-4.029E-01	9.999E+27	1.592E+25
1.5848E+01	2.517E+02	-4.040E-01	9.999E+27	1.592E+25
2.5118E+01	2.517E+02	-4.058E-01	9.999E+27	-1.592E+25
3.9810E+01	2.517E+02	-4.087E-01	9.999E+27	-1.592E+25
6.3095E+01	2.517E+02	-4.133E-01	9.999E+27	-1.592E+25
1.0000E+02	2.517E+02	-4.204E-01	9.999E+27	1.592E+25
1.5848E+02	2.517E+02	-4.319E-01	9.999E+27	1.592E+25
2.5118E+02	2.517E+02	-4.500E-01	9.999E+27	1.592E+25
3.9810E+02	2.517E+02	-4.787E-01	9.999E+27	-1.592E+25
6.3095E+02	2.517E+02	-5.241E-01	9.999E+27	1.592E+25
1.0000E+03	2.517E+02	-5.962E-01	9.999E+27	-1.592E+25
1.5848E+03	2.517E+02	-7.104E-01	9.999E+27	1.592E+25
2.5118E+03	2.517E+02	-8.914E-01	9.999E+27	-1.592E+25
3.9810E+03	2.517E+02	-1.178E+00	9.999E+27	1.592E+25
6.3095E+03	2.517E+02	-1.632E+00	9.999E+27	-1.592E+25
1.0000E+04	2.517E+02	-2.353E+00	9.999E+27	1.592E+25
1.5848E+04	2.517E+02	-3.495E+00	9.999E+27	1.592E+25
2.5118E+04	2.516E+02	-5.303E+00	9.999E+27	1.592E+25
3.9810E+04	2.515E+02	-8.166E+00	9.999E+27	1.592E+25
6.3095E+04	2.511E+02	-1.269E+01	9.999E+27	-1.592E+25
1.0000E+05	2.502E+02	-1.980E+01	9.999E+27	-1.592E+25
1.5848E+05	2.479E+02	-3.088E+01	9.999E+27	1.592E+25
2.5118E+05	2.424E+02	-4.763E+01	9.999E+27	1.592E+25
3.9810E+05	2.297E+02	-7.132E+01	9.999E+27	-1.592E+25
6.3095E+05	2.029E+02	-9.970E+01	9.999E+27	-1.592E+25
1.0000E+06	1.569E+02	-1.221E+02	9.999E+27	1.592E+25
1.5848E+06	1.000E+02	-1.233E+02	9.999E+27	-1.592E+25
2.5118E+06	5.235E+01	-1.023E+02	9.999E+27	-1.592E+25
3.9810E+06	2.380E+01	-7.378E+01	9.999E+27	1.592E+25
6.3095E+06	1.003E+01	-4.936E+01	9.999E+27	1.592E+25
1.0000E+07	4.085E+00	-3.191E+01	9.999E+27	-1.592E+25
1.5848E+07	1.636E+00	-2.033E+01	9.999E+27	1.592E+25
2.5118E+07	6.503E-01	-1.288E+01	9.999E+27	1.592E+25

Return Ratio versus Freq.

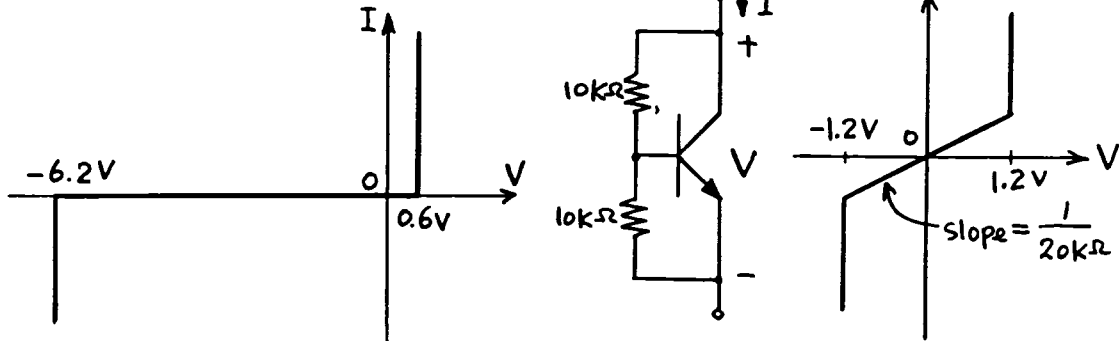


9.45 (a) See above.
 (b) The unity-gain frequency is ~ 400 MHz.
 The phase margin is $\sim 90^\circ$.
 The gain margin is ∞ (the phase never reaches -180°).

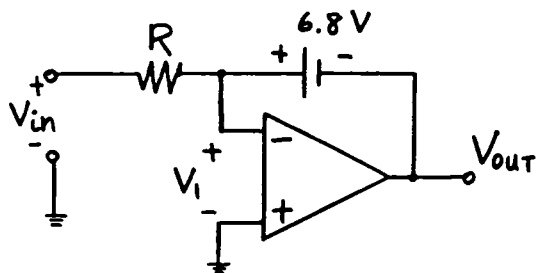
CHAPTER 10

10.1

Zener diode characteristic

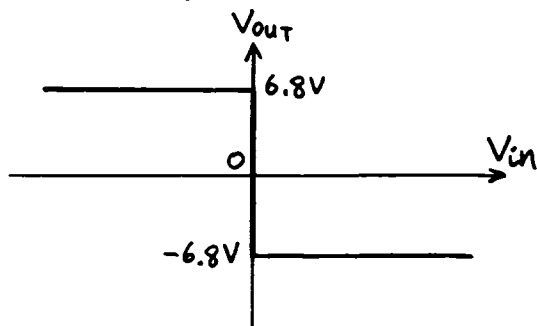


For V_{in} positive, V_{out} is negative and we have



Since $V_i = 0$, $V_{out} = -6.8V$

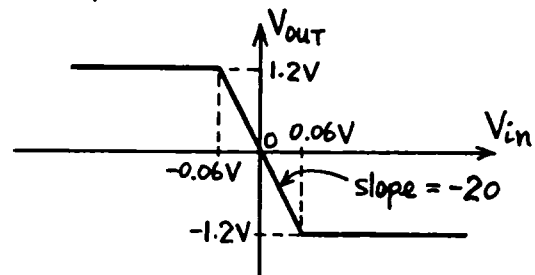
For V_{in} negative, $V_{out} = +6.8V$



For V_{out} between $\pm 1.2V$, the transistor is off and

$$\frac{\Delta V_{out}}{\Delta V_{in}} = -\frac{20k\Omega}{1k\Omega} = -20$$

Outside this range, V_{out} is clamped to $\pm 1.2V$



10.2

Consider the V_{BE} -multiplier.

$\therefore$ symmetrical transistor, $\therefore$

CKT FOR PROBLEM 10.2

```

R1W 1 2 1K
Q1 4 3 2 N
R1 4 3 10K
R2 3 2 10K
ROP_AMP 4 0 2 0 -10000
VIN 1 0 0V
.MODEL N NPN BF=99 BR=99 IS=1E-16
.PLOT DC V(4)
.DC VIN -0.1 0.1 0.01
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** DC TRANSFER CURVES THOM= 27.000 TEMP= 27.000

VOLT	V(4)					
(A)		-2.000E+00	-1.000E-00	0.	1.000E-00	2.000E+00
-1.000E-01	1.37E+00					
-9.000E-02	1.35E+00					
-8.000E-02	1.32E+00					
-7.000E-02	1.28E+00					
-6.000E-02	1.18E+00					
-5.000E-02	9.97E-01					
-4.000E-02	7.98E-01					
-3.000E-02	5.99E-01					
-2.000E-02	3.99E-01					
-1.000E-02	2.00E-01					
0.	0.					
1.000E-02	-2.00E-01					
2.000E-02	-3.99E-01					
3.000E-02	-5.99E-01					
4.000E-02	-7.98E-01					
5.000E-02	-9.97E-01					
6.000E-02	-1.18E+00					
7.000E-02	-1.28E+00					
8.000E-02	-1.32E+00					
9.000E-02	-1.35E+00					
1.000E-01	-1.37E+00					

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

```

+0:1 = 0. 0:2 = 0. 0:3 = 0.
+0:4 = 0.

```

**** BIPOLAR JUNCTION TRANSISTORS

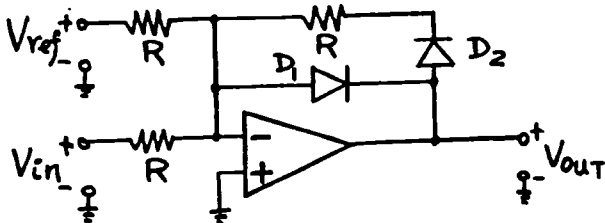
```

ELEMENT 0:Q1
MODEL 0:M
IB 0.
IC 0.
VBE 0.
VCE 0.
VBC 0.
VS 0.
POWER 0.
RETA0 0.
GM 0.
RPI 2.560E+16
RX 0.
RO 2.586E+14
CPI 0.
CMU 0.
CEX 0.
CCS 0.
RETA0C 0.
FT 6.216E-03

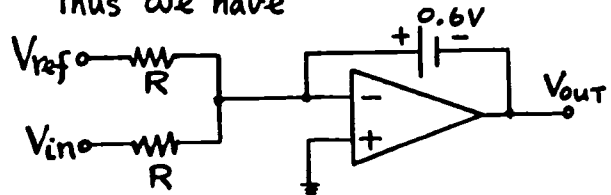
```

10.3

For $V_{in} > -V_{ref}$, the input to the op amp is positive, and V_{out} is negative. $\therefore D_1$ is on, D_2 is off.

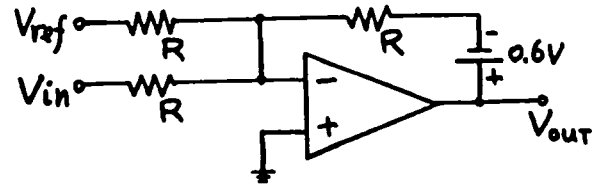


Thus we have

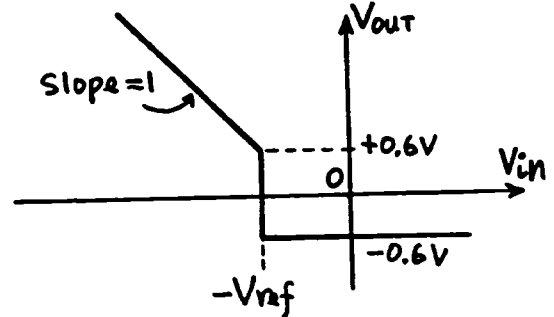


$$V_{out} = -0.6V$$

For $V_{in} < -V_{ref}$, V_{out} is positive and D_2 is on, D_1 is off.



$$V_{out} = 0.6 + V_{in} + V_{ref}$$



10.4

The multiplier transfer function is $I_{out} = I_{c3-5} - I_{c4-6}$

$$= I_{EE} \tanh \frac{V_1}{2V_T} \tanh \frac{V_2}{2V_T}$$

For $V_1 = 0.1V_T$

$$I_{out} = I_{EE} \times 0.050 \tanh \frac{V_2}{2V_T}$$

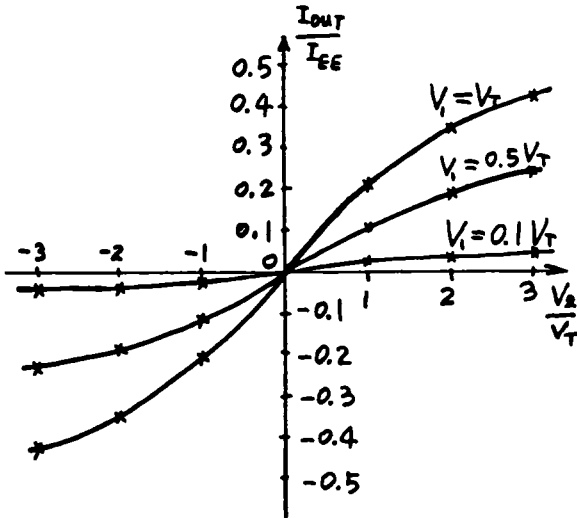
$$V_1 = 0.5V_T$$

$$I_{out} = I_{EE} \times 0.245 \tanh \frac{V_2}{2V_T}$$

$$V_1 = V_T$$

$$I_{out} = I_{EE} \times 0.462 \tanh \frac{V_2}{2V_T}$$

10-3



10.5

For the emitter coupled pair

$$\Delta I_c = I_{c1} - I_{c2} = I_{EE} \tanh\left(\frac{V_{id}}{2V_T}\right)$$

$$= I_{EE} \frac{e^{\frac{V_{id}}{V_T}} - 1}{e^{\frac{V_{id}}{V_T}} + 1}$$

The slope of the characteristic is

$$\begin{aligned} \frac{d(\Delta I_c)}{dV_{id}} &= \frac{I_{EE}}{V_T} \frac{\left(e^{\frac{V_{id}}{V_T}} + 1\right)e^{\frac{V_{id}}{V_T}} - \left(e^{\frac{V_{id}}{V_T}} - 1\right)e^{\frac{V_{id}}{V_T}}}{\left(e^{\frac{V_{id}}{V_T}} + 1\right)^2} \\ &= \frac{I_{EE}}{V_T} \frac{2e^{\frac{V_{id}}{V_T}}}{\left(e^{\frac{V_{id}}{V_T}} + 1\right)^2} \quad \text{----- (1)} \end{aligned}$$

For $V_{id} = 0$

$$\frac{d(\Delta I_c)}{dV_{id}} = \frac{1}{2} \frac{I_{EE}}{V_T}$$

$$\text{In (1) put } \frac{d(\Delta I_c)}{dV_{id}} = 0.99 \times \frac{1}{2} \times \frac{I_{EE}}{V_T}$$

$$\therefore 0.99 = 4 \frac{a}{(a+1)^2} \quad \text{where } a = e^{\frac{V_{id}}{V_T}}$$

$$\therefore a^2 + 2a + 1 = \frac{4}{0.99} a$$

$$\therefore a^2 - 2.0404a + 1 = 0$$

$$\therefore a = \frac{2.0404 \pm \sqrt{4.1632 - 4}}{2}$$

$$= 1.222 \text{ or } 0.8182$$

$$\therefore V_{id} = \pm 0.2V_T = \pm 5 \text{ mV}$$

10.6

$$\Delta I_c = I_{EE} \tanh\left(\frac{V_{id}}{2V_T}\right)$$

$$\simeq I_{EE} \left[\frac{V_{id}}{2V_T} - \frac{1}{3} \left(\frac{V_{id}}{2V_T} \right)^3 \right]$$

$$\text{Put } V_{id} = V \sin \omega_0 t$$

Then

$$\Delta I_c = \frac{I_{EE}}{2V_T} \left[V \sin \omega_0 t - \frac{1}{12} \frac{V^3}{V_T^2} \sin^3 \omega_0 t \right]$$

$$= \frac{I_{EE} V}{2V_T} \left[\sin \omega_0 t - \frac{V^3}{48 V_T^2} (3 \sin \omega_0 t - \sin 3 \omega_0 t) \right]$$

$$\therefore I_{OUT}(t) = I_0 \left[\sin \omega_0 t + \frac{\frac{V^2}{48 V_T^2}}{1 - 3 \frac{V^2}{48 V_T^2}} \sin 3 \omega_0 t \right]$$

$$\text{Put } \frac{\frac{V^2}{48 V_T^2}}{1 - 3 \frac{V^2}{48 V_T^2}} = 0.01$$

$$\therefore V = 17.7 \text{ mV}$$

This is the maximum allowable input amplitude.

10-4

```

EMITTER-COUPLED PAIR
VCC 1 0 5V
VDUMMY 1 11 0V
Q1 11 3 2 N
Q2 1 4 2 N
IIE 2 0 1MA
VIN 3 0 SIN 0 17.7MV 10K
VIN2 4 0 0V
.MODEL N NPN
.PLOT TRAN I(VDUMMY)
.TRAN 0.005MS 0.2MS
.FOUR 10K I(VDUMMY)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

```

+0:1 = 5.000E+00 0:2 = -7.560E-01 0:3 = 0.
+0:4 = 0. 0:11 = 5.000E+00

```

**** BIPOLAR JUNCTION TRANSISTORS

```

ELEMENT 0:Q1 0:Q2
MODEL 0:N 0:N
IB 4.950E-06 4.950E-06
IC 4.950E-04 4.950E-04
VBE 7.560E-01 7.560E-01
VCE 5.756E+00 5.756E+00
VBC -5.000E+00 -5.000E+00
VS -5.000E+00 -5.000E+00
POWER 2.853E-03 2.853E-03
BETAD 1.000E+02 1.000E+02
GM 1.914E-02 1.914E-02
RPI 5.224E+03 5.224E+03
RX 0. 0.
RO 5.000E+16 5.000E+16
CPI 0. 0.
CMU 0. 0.
CBX 0. 0.
CCS 0. 0.
BETAAC 9.999E+01 9.999E+01
FT 3.046E+12 3.046E+12

```

***** TRANSIENT ANALYSIS THOM= 27.000 TEMP= 27.000

```

TIME I(VDUMMY)
(A) 3.000E-04 4.000E-04 5.000E-04 6.000E-04 7.000E-04
0. 4.95E-04 + + + + +
5.000E-06 5.47E-04 + + + + + A + + +
1.000E-05 5.93E-04 + + + + + A+ + + +
1.500E-05 6.29E-04 + + + + + A + + +
2.000E-05 6.50E-04 + + + + + A + + +
2.500E-05 6.58E-04 + + + + + A + + +
3.000E-05 6.50E-04 + + + + + A + + +
3.500E-05 6.29E-04 + + + + + A + + +
4.000E-05 5.92E-04 + + + + + A+ + + +
4.500E-05 5.47E-04 + + + + + A + + +
5.000E-05 4.95E-04 + + + + + A + + +
5.500E-05 4.43E-04 + + + + + A+ + + +
6.000E-05 3.97E-04 + + + + + + + + +
6.500E-05 3.61E-04 + A + + + + + + +
7.000E-05 3.41E-04 + A+ + + + + + +
7.500E-05 3.32E-04 + A + + + + + + +
8.000E-05 3.41E-04 + A+ + + + + + +
8.500E-05 3.61E-04 + A + + + + + + +
9.000E-05 3.98E-04 + + A + + + + + +
9.500E-05 4.43E-04 + + + A+ + + + + +
1.000E-04 4.95E-04 + + + + + A+ + + +
1.050E-04 5.47E-04 + + + + + A + + +
1.100E-04 5.93E-04 + + + + + A+ + + +
1.150E-04 6.29E-04 + + + + + + A + +
1.200E-04 6.50E-04 + + + + + + A +
1.250E-04 6.58E-04 + + + + + + A+ +
1.300E-04 6.50E-04 + + + + + + A +
1.350E-04 6.29E-04 + + + + + + A +
1.400E-04 5.92E-04 + + + + + A+ + +
1.450E-04 5.47E-04 + + + + + A + + +
1.500E-04 4.95E-04 + + + + + A+ + + +
1.550E-04 4.43E-04 + + + + + A+ + + +
1.600E-04 3.97E-04 + + A + + + + + +
1.650E-04 3.61E-04 + A + + + + + + +
1.700E-04 3.41E-04 + A+ + + + + + +
1.750E-04 3.32E-04 + A + + + + + + +
1.800E-04 3.41E-04 + A+ + + + + + +
1.850E-04 3.61E-04 + A + + + + + + +
1.900E-04 3.98E-04 + + A + + + + + +
1.950E-04 4.43E-04 + + + A+ + + + + +
2.000E-04 4.95E-04 + + + + + A+ + + +

```

FOURIER COMPONENTS OF TRANSIENT RESPONSE I(VDUMMY)

DC COMPONENT = 4.950D-04

HARMONIC FREQUENCY FOURIER NORMALIZED PHASE NORMALIZED

NO	(HZ)	COMPONENT	COMPONENT	(DEG)	PHASE (DEG)
1	9.999E+03	1.640E-04	1.000E+00	-7.158E-03	0.
2	2.000E+04	1.607E-08	9.800E-05	1.195E-01	1.267E-01
3	3.000E+04	1.421E-06	8.664E-03	1.655E+00	1.662E+00
4	4.000E+04	2.449E-09	1.493E-05	2.509E+00	2.516E+00
5	5.000E+04	5.072E-08	3.093E-04	1.324E+02	1.324E+02
6	6.000E+04	3.553E-10	2.166E-06	3.370E+00	3.378E+00
7	7.000E+04	2.602E-08	1.586E-04	-1.432E+02	-1.432E+02
8	8.000E+04	1.085E-09	6.615E-06	-1.973E+01	-1.973E+01
9	9.000E+04	1.752E-07	1.068E-03	-1.926E+01	-1.925E+01

TOTAL HARMONIC DISTORTION = 8.737E-01 PERCENT

EMITTER-COUPLED PAIR WITH EMITTER DEGENERATION

```

VCC 1 0 5V
VDUMMY 1 7 0V
Q1 7 3 5 N
Q2 1 4 6 N
RE1 5 2 200
RE2 6 2 200
IIE 2 0 1MA
VIN 3 0 SIN 0 17.7MV 10K
VIN2 4 0 0V
.MODEL N NPN
.PLOT TRAN I(VDUMMY)
.TRAN 0.005MS 0.2MS
.FOUR 10K I(VDUMMY)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

```

+0:1 = 5.000E+00 0:2 = -8.560E-01 0:3 = 0.
+0:4 = 0. 0:5 = -7.560E-01 0:6 = -7.560E-01
+0:7 = 5.000E+00

```

**** BIPOLAR JUNCTION TRANSISTORS

```

ELEMENT 0:Q1 0:Q2
MODEL 0:N 0:N
IB 4.950E-06 4.950E-06
IC 4.950E-04 4.950E-04
VBE 7.560E-01 7.560E-01
VCE 5.756E+00 5.756E+00
VBC -5.000E+00 -5.000E+00
VS -5.000E+00 -5.000E+00
POWER 2.853E-03 2.853E-03
BETAD 1.000E+02 1.000E+02
GM 1.914E-02 1.914E-02
RPI 5.224E+03 5.224E+03
RX 0. 0.
RO 5.000E+16 5.000E+16
CPI 0. 0.
CMU 0. 0.
CBX 0. 0.
CCS 0. 0.
BETAAC 9.999E+01 9.999E+01
FT 3.046E+12 3.046E+12

```

10-5

***** TRANSIENT ANALYSIS

TWO= 27.000 TEMP= 27.000

TIME	I(VDUMMY)								
(A)		4.600E-04	4.800E-04	5.000E-04	5.200E-04	5.400E-04			
0.	4.95E-04	+	+	+	+	+	+	+	+
5.000E-06	5.06E-04	+	+	+	+	+	+	+	+
1.000E-05	5.15E-04	+	+	+	+	+	+	+	+
1.500E-05	5.23E-04	+	+	+	+	+	+	+	+
2.000E-05	5.28E-04	+	+	+	+	+	+	+	+
2.500E-05	5.30E-04	+	+	+	+	+	+	+	+
3.000E-05	5.28E-04	+	+	+	+	+	+	+	+
3.500E-05	5.23E-04	+	+	+	+	+	+	+	+
4.000E-05	5.15E-04	+	+	+	+	+	+	+	+
4.500E-05	5.06E-04	+	+	+	+	+	+	+	+
5.000E-05	4.95E-04	+	+	+	+	+	+	+	+
5.500E-05	4.84E-04	+	+	+	+	+	+	+	+
6.000E-05	4.75E-04	+	+	+	+	+	+	+	+
6.500E-05	4.67E-04	+	+	+	+	+	+	+	+
7.000E-05	4.62E-04	+	+	+	+	+	+	+	+
7.500E-05	4.60E-04	+	+	+	+	+	+	+	+
8.000E-05	4.62E-04	+	+	+	+	+	+	+	+
8.500E-05	4.67E-04	+	+	+	+	+	+	+	+
9.000E-05	4.75E-04	+	+	+	+	+	+	+	+
9.500E-05	4.84E-04	+	+	+	+	+	+	+	+
1.000E-04	4.95E-04	+	+	+	+	+	+	+	+
1.050E-04	5.06E-04	+	+	+	+	+	+	+	+
1.100E-04	5.15E-04	+	+	+	+	+	+	+	+
1.150E-04	5.23E-04	+	+	+	+	+	+	+	+
1.200E-04	5.28E-04	+	+	+	+	+	+	+	+
1.250E-04	5.30E-04	+	+	+	+	+	+	+	+
1.300E-04	5.28E-04	+	+	+	+	+	+	+	+
1.350E-04	5.23E-04	+	+	+	+	+	+	+	+
1.400E-04	5.15E-04	+	+	+	+	+	+	+	+
1.450E-04	5.06E-04	+	+	+	+	+	+	+	+
1.500E-04	4.95E-04	+	+	+	+	+	+	+	+
1.550E-04	4.84E-04	+	+	+	+	+	+	+	+
1.600E-04	4.75E-04	+	+	+	+	+	+	+	+
1.650E-04	4.67E-04	+	+	+	+	+	+	+	+
1.700E-04	4.62E-04	+	+	+	+	+	+	+	+
1.750E-04	4.60E-04	+	+	+	+	+	+	+	+
1.800E-04	4.62E-04	+	+	+	+	+	+	+	+
1.850E-04	4.67E-04	+	+	+	+	+	+	+	+
1.900E-04	4.75E-04	+	+	+	+	+	+	+	+
1.950E-04	4.84E-04	+	+	+	+	+	+	+	+
2.000E-04	4.95E-04	+	+	+	+	+	+	+	+

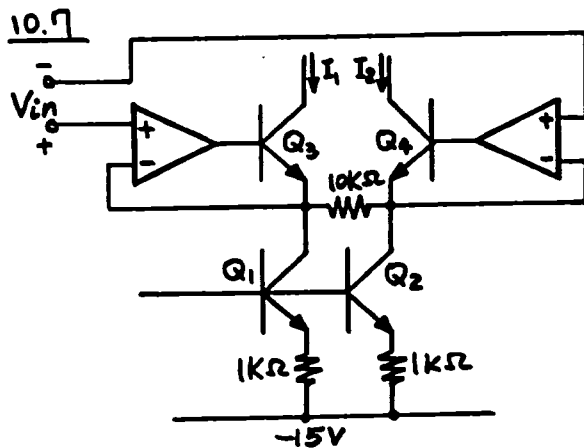
FOURIER COMPONENTS OF TRANSIENT RESPONSE I(VDUMMY)

DC COMPONENT = 4.950D-04

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	3.467E-05	1.000E+00	-7.119E-03	0.
2	2.000E+04	3.142E-09	9.063E-05	1.159E-01	1.230E-01
3	3.000E+04	1.601E-08	4.616E-04	1.509E+02	1.509E+02
4	4.000E+04	2.206E-10	6.361E-06	5.205E+00	5.213E+00
5	5.000E+04	1.067E-08	3.078E-04	1.394E+02	1.394E+02
6	6.000E+04	3.660E-11	1.055E-06	6.605E+00	6.612E+00
7	7.000E+04	6.790E-09	1.958E-04	-1.576E+02	-1.576E+02
8	8.000E+04	2.139E-10	6.168E-06	-2.165E+01	-2.165E+01
9	9.000E+04	3.783E-08	1.091E-03	-1.996E+01	-1.995E+01

TOTAL HARMONIC DISTORTION = 1.243E-01 PERCENT

10-6



The nominal bias currents are

$$I_{C1} = I_{C2} = I_{C3} = I_{C4} = 1 \text{ mA}$$

Given $\frac{\Delta R}{R} = \pm 0.3\%$, $\frac{\Delta I_S}{I_S} = \pm 2\%$

From (4.154) the worst-case mismatch in I_{C1} and I_{C2} is

$$\begin{aligned} \left| \frac{\Delta I_C}{I_C} \right| &= \frac{1}{1 + \frac{I_S}{I_C}} \frac{\Delta I_S}{I_S} + \frac{I_S}{1 + \frac{I_S}{I_C}} \frac{\Delta R}{R} \\ &= \frac{1}{1 + \frac{1000}{26}} 0.02 + \frac{\frac{1000}{26}}{1 + \frac{1000}{26}} 0.003 \\ &= 3.43 \times 10^{-3} \end{aligned}$$

$$\begin{aligned} \therefore \Delta I_C &= 3.43 \times 10^{-3} \times 10^{-3} \text{ A} \\ &= 3.43 \mu\text{A} \end{aligned}$$

This gives an input offset (when $I_1 = I_2$) of

$$\begin{aligned} V_{OS} &= \frac{\Delta I_C}{2g_m} = 3.43 \mu\text{A} \times 10 \text{ k}\Omega \times \frac{1}{2} \\ &= 17.1 \text{ mV} \end{aligned}$$

Offset due to Q_3 and Q_4 is negligible because of the ideal op amps.

10-7

VOLTAGE-CURRENT CONVERTER

```

VCC 1 0 15V
VDDUMY 1 14 0V
VSS 2 0 -15V
Q1 14 7 5 N
Q2 1 8 6 N
KEE 5 6 10K
Q3 5 11 9 N
Q4 6 11 10 N
R1 9 2 1K
R2 10 2 1K
R3 12 2 1K
IBIAS 1 13 1MA
Q5 13 11 12 N
Q6 1 13 11 N
KAMP1 7 0 4 5 10000
KAMP2 8 0 3 6 10000
VS 3 0 SIN 0 5V 10K
EVS 4 0 3 0 -1
KX1 3 0 100MEG
KX2 4 0 100MEG
.MODEL N NPN IS=1E-16
.PLOT TRAN I(VDDUMY)
.TRAN 0.005MS 0.2MS
.FOUR 10K I(VDDUMY)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

```

+0:1 = 1.500E+01 0:2 = -1.500E+01 0:3 = 0.
+0:4 = 0. 0:5 = -7.739E-05 0:6 = -7.739E-05
+0:7 = 7.739E-01 0:8 = 7.739E-01 0:9 = -1.399E+01
+0:10 = -1.399E+01 0:11 = -1.321E+01 0:12 = -1.399E+01
+0:13 = -1.253E+01 0:14 = 1.500E+01

```

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	Q:Q1	Q:Q2	Q:Q3	Q:Q4	Q:Q5	Q:Q6
MODEL	Q:M	Q:M	Q:M	Q:M	Q:M	Q:M
IB	9.898E-06	9.898E-06	9.997E-06	9.997E-06	9.997E-06	2.969E-07
IC	9.898E-04	9.898E-04	9.997E-04	9.997E-04	9.997E-04	2.969E-05
VBE	7.739E-01	7.739E-01	7.742E-01	7.742E-01	7.742E-01	6.832E-01
VCE	1.500E+01	1.500E+01	1.399E+01	1.399E+01	1.457E+00	2.821E+01
VBC	-1.422E+01	-1.422E+01	-1.321E+01	-1.321E+01	-6.832E-01	-2.753E+01
VS	-1.500E+01	-1.500E+01	7.739E-05	7.739E-05	1.253E+01	-1.500E+01
POWER	1.485E-02	1.485E-02	1.399E-02	1.399E-02	1.465E-03	8.381E-04
BETAD	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02
GM	3.827E-02	3.827E-02	3.865E-02	3.865E-02	3.865E-02	1.148E-03
RPI	2.613E+03	2.613E+03	2.587E+03	2.587E+03	2.587E+03	8.710E+04
KX	0.	0.	0.	0.	0.	0.
RO	1.422E+17	1.422E+17	1.321E+17	1.321E+17	6.832E+15	2.753E+17
CPI	0.	0.	0.	0.	0.	0.
CMU	0.	0.	0.	0.	0.	0.
CBX	0.	0.	0.	0.	0.	0.
CCS	0.	0.	0.	0.	0.	0.
BETAC	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01
FT	6.090E+12	6.090E+12	6.151E+12	6.151E+12	6.151E+12	1.827E+11

***** TRANSIENT ANALYSIS

THOM= 27.000 TEMP= 27.000

TIME	I(VDDUMY)	0.	5.000E-04	1.000E-03	1.500E-03	2.000E-03
0.	9.90E-04	+	+	+	+	+
5.000E-06	6.84E-04	+	+	A	+	+
1.000E-05	4.12E-04	+	A	+	+	+
1.500E-05	1.89E-04	A	+	+	+	+
2.000E-05	5.57E-05	A	+	+	+	+
2.500E-05	3.89E-11	A	+	+	+	+
3.000E-05	4.85E-05	A	+	+	+	+
3.500E-05	1.89E-04	A	+	+	+	+
4.000E-05	4.12E-04	+	A	+	+	+
4.500E-05	6.84E-04	+	+	A	+	+
5.000E-05	9.90E-04	+	+	+	A	+
5.500E-05	1.29E-03	+	+	+	+	A
6.000E-05	1.57E-03	+	+	+	+	+
6.500E-05	1.79E-03	+	+	+	+	A
7.000E-05	1.92E-03	+	+	+	+	+
7.500E-05	1.98E-03	+	+	+	+	A
8.000E-05	1.93E-03	+	+	+	+	+
8.500E-05	1.79E-03	+	+	+	+	A
9.000E-05	1.57E-03	+	+	+	+	+
9.500E-05	1.29E-03	+	+	+	A	+
1.000E-04	9.90E-04	+	+	+	+	A
1.050E-04	6.84E-04	+	+	A	+	+
1.100E-04	4.12E-04	+	A	+	+	+
1.150E-04	1.89E-04	A	+	+	+	+
1.200E-04	5.57E-05	A	+	+	+	+
1.250E-04	3.89E-11	A	+	+	+	+
1.300E-04	4.85E-05	A	+	+	+	+
1.350E-04	1.89E-04	A	+	+	+	+
1.400E-04	4.12E-04	+	A	+	+	+
1.450E-04	6.84E-04	+	+	A	+	+
1.500E-04	9.90E-04	+	+	+	A	+
1.550E-04	1.29E-03	+	+	+	+	A
1.600E-04	1.57E-03	+	+	+	+	+
1.650E-04	1.79E-03	+	+	+	+	A
1.700E-04	1.92E-03	+	+	+	+	+
1.750E-04	1.98E-03	+	+	+	+	A
1.800E-04	1.93E-03	+	+	+	+	+
1.850E-04	1.79E-03	+	+	+	+	A
1.900E-04	1.57E-03	+	+	+	+	+
1.950E-04	1.29E-03	+	+	+	A	+
2.000E-04	9.90E-04	+	+	+	+	A

***** FOURIER COMPONENTS OF TRANSIENT RESPONSE I(VDDUMY)

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	9.870E-04	1.000E+00	1.799E+02	0.
2	2.000E+04	8.858E-08	8.974E-05	1.735E+02	-6.391E+00
3	3.000E+04	1.121E-06	1.135E-03	-4.055E+01	-2.205E+02
4	4.000E+04	1.752E-08	1.775E-05	-1.310E+02	-3.110E+02
5	5.000E+04	4.472E-07	4.531E-04	6.031E+01	-1.196E+02
6	6.000E+04	1.803E-08	1.827E-05	4.726E+01	-1.327E+02
7	7.000E+04	3.780E-07	3.830E-04	-1.080E+02	-2.880E+02
8	8.000E+04	2.962E-08	3.001E-05	-1.678E+02	-3.478E+02
9	9.000E+04	7.880E-07	7.983E-04	1.381E+02	-4.179E+01

TOTAL HARMONIC DISTORTION = 1.513E-01 PERCENT

10.8

Assuming an ideal op amp.

$$\frac{V_{in}}{R} = -\frac{V_z}{R} \therefore V_z = -V_{in}$$

$$\text{But } V_z = K V_x V_y = K V_{out} V_{REF}$$

$$\text{Thus } V_{out} = \frac{-V_{in}}{K V_{REF}}$$

and this circuit produces an output proportional to the quotient of two voltages.

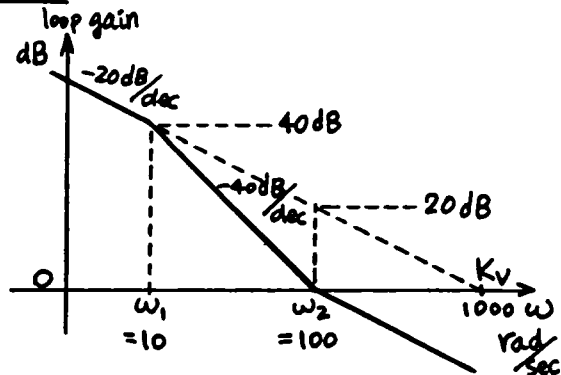
10.9

$$\text{Loop bandwidth} = K_V = K_0 K_D \\ = 10^3 \text{ } 1/s$$

In order to produce poles at 45° to the axis, we add a loop filter

pole at ω_1 where

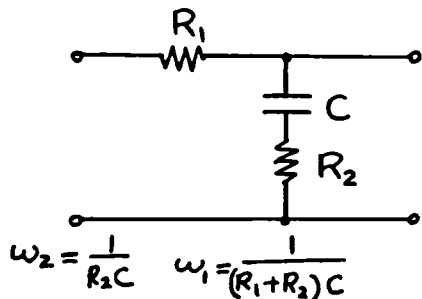
$$\omega_1 = 2K_V = 2000 \text{ rad/s}$$

10.10

If ω_2 (the zero frequency) is at the unity gain point, then the loop phase shift will be -135° at this point, $\therefore$ we require $\omega_2 = 100 \text{ rad/sec}$

If $\omega_1 = 10 \text{ rad/sec}$, the requirements will be satisfied (see diagram)

The filter becomes



$$\therefore \frac{\omega_2}{\omega_1} = 1 + \frac{R_1}{R_2} = 10$$

$$\therefore R_1 = 9 R_2$$

Appropriate values of R_1, R_2 and C can now be chosen.

10.11

For capture we need

$$|(\omega_i - \omega_0)| < \frac{\pi}{2} K_V |F[j(\omega_i - \omega_0)]|$$

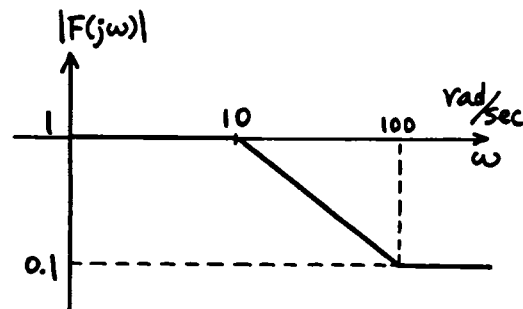
$$\text{Put } |(\omega_i - \omega_0)| = \frac{\pi}{2} K_V |F[j(\omega_i - \omega_0)]|$$

$$\omega_0 = 10^5 \text{ rad/sec}$$

$$K_V = 1000 \text{ rad/sec}$$

$$\therefore |(\omega_i - \omega_0)| = 1570 |F[j(\omega_i - \omega_0)]| \quad \text{----- (1)}$$

From Problem 10.10



From the figure we can solve (1) to find

$$(\omega_i - \omega_0) = 157 \text{ rad/sec}$$

and this is the capture range.

10.12

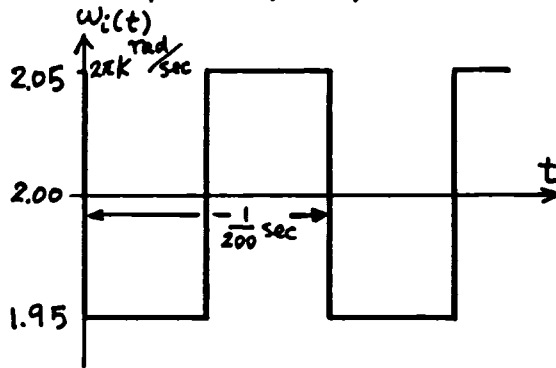
For the 560B

$$K_0 = 0.93 \omega_0 = 0.93 (2\pi) (2000) \\ = 11687 \text{ rad/V.s}$$

$$K_V = 2.36 \omega_0 = 2.36 (2\pi) (2000) \\ = 29657 \text{ rad/s}$$

10-9

The input frequency is



$$\frac{V_o}{w_i}(s) = \frac{1}{K_o} \frac{K_v}{s + K_v} \text{ ----- (1)}$$

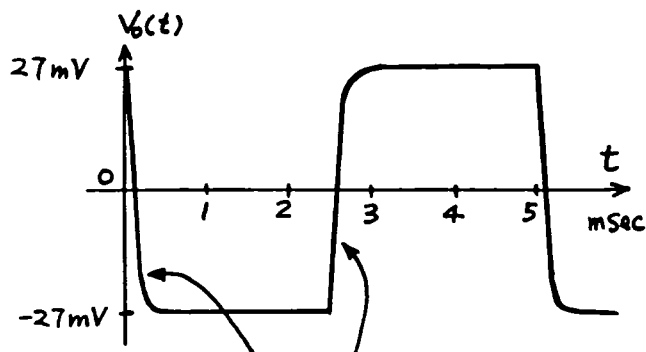
The peak-to-peak amplitude of the output is

$$\Delta V_o = \frac{\Delta w_i}{K_o} = \frac{2\pi(100)}{11687} = 54 \text{ mV}$$

Since $w_i(t)$ is a square wave,

(1) predicts that $V_o(t)$ has a time constant

$\frac{1}{K_v} = 34 \mu\text{s}$ and the waveform shown below.



time constant = $34 \mu\text{s}$

10-10

10.13

$$f = \frac{I_1}{4C V_{BE(ON)}}$$

$$I_1 = (10 \text{ kHz})(4)(0.01 \mu\text{F})(0.7 \text{ V})$$

$$= 280 \mu\text{A} \quad \uparrow \text{guess}$$

$$V_{BE} = V_T \ln \frac{2(280 \mu\text{A})}{10^{-16}}$$

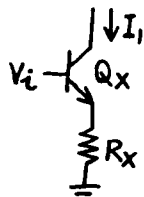
$$= 0.763 \text{ V}$$

$$I_1 = 305 \mu\text{A} \text{ at center freq}$$

for 2:1 variation of freq,

$$\text{vary } I_1 = 203 \text{ to } 407 \mu\text{A}$$

$$\Delta I_1 = 204 \mu\text{A}$$



$$I_1 = \frac{V_i - V_{BEX}}{R_x}$$

dc bias:

$$I_1 = 305 \mu = \frac{V_i - 0.763}{R_x}$$

$$\Delta I_1 \approx \frac{\Delta V_i}{R_x}$$

$$204 \mu = \frac{200 \text{ mV}}{R_x}$$

$$R_x = 1 \text{ k}$$

$$\text{dc bias } I_1 = 305 \mu = \frac{V_i - 0.763}{1 \text{ k}}$$

$$\text{bias } V_i = 1.07 \text{ V}$$

make current in R small
compared to $2I_1$

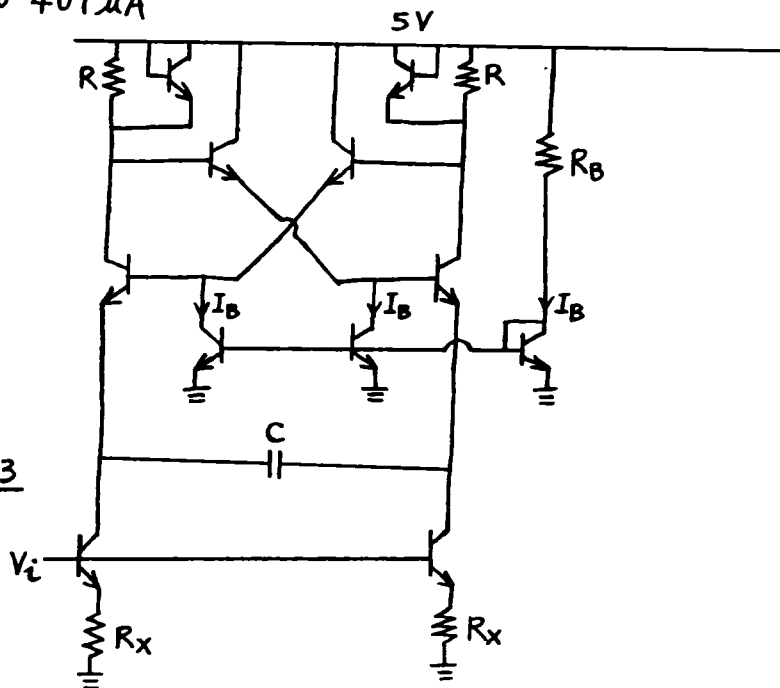
$$\frac{V_{BE}}{R} = 60 \mu\text{A}$$

$$R = \frac{0.763 \text{ V}}{60 \mu\text{A}} = 12.7 \text{ k}$$

 I_B is bias only. $I_B = 200 \mu\text{A}$ is adequate.

$$I_B = \frac{5 - V_T \ln \frac{200 \mu}{10^{-16}}}{R_B} = 200 \mu$$

$$R_B = 21.3 \text{ k}$$



10-11

```

*****
* SUMMARY
* VI (V)      OSCILLATION FREQ (KHZ)
* 0.97        10
* 1.07        14.3
* 1.17        18.2
*****
* OSCILLATION FREQ VARIATION = 18.2:10 = 1.82:1
*****
* VI = BIAS = 1.07V
* EXPECTED OSCILLATION FREQUENCY = 10 KHZ
* PERIOD = 100 US
* ACTUAL OSCILLATION FREQUENCY = 14.3 KHZ
* PERIOD = 70 US
* THIS DIFFERENCE IS DUE TO THE ERROR IN HAND-CALCULATING
* THE VBE AND INPUT CURRENT I1 WHICH IS DIRECTLY
* PROPORTIONAL TO THE OSCILLATION FREQUENCY.
*****
* VOLTAGE CONTROLLED OSCILLATOR
VCC 1 0 5V
Q1 7 10 5 M
Q2 8 9 6 M
Q3 1 7 9 M
Q4 1 8 10 M
Q5 1 1 7 M
Q6 1 1 8 M
Q7 5 2 3 M
Q8 6 2 4 M
R1 1 7 12.7K
R2 1 8 12.7K
R3 3 0 1K
R4 4 0 1K
Q9 10 13 0 M
Q10 9 13 0 M
Q11 13 13 0 M
R5 1 13 21.3K
* ADDED A SMALL CAPACITOR BETWEEN NODES 7,8
CAP 5 61 0.01UF
VI 2 0 1.07V
* ADDED A SERIES PWL VOLTAGE TO LOAD CAP TO SET IC
VICK 61 6 PWL 0 100N 100N 1.01US 0
CX1 7 8 0.01NF
.MODEL N NPN BF=100 IS=1E-16
.PLOT V(6,5)
.TRAN 500US
.OPTIONS NOPAGE NOMOD LIMPTS=700
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

***** OPERATING POINT STATUS IS ALL SIMULATION TIME IS 0.
+0:1 = 5.000E+00 0:2 = 1.070E+00 0:3 = 3.251E-01
+0:4 = 3.251E-01 0:5 = 2.784E+00 0:6 = 2.784E+00
+0:7 = 4.260E+00 0:8 = 4.260E+00 0:9 = 3.528E+00
+0:10 = 3.528E+00 0:13 = 7.319E-01 0:61 = 2.884E+00

**** BIPOLAR JUNCTION TRANSISTORS
ELEMENT 0:Q1 0:Q2 0:Q3 0:Q4 0:Q5 0:Q6
MODEL 0:M 0:M 0:M 0:M 0:M 0:M
IB 3.187E-06 3.187E-06 1.958E-06 1.958E-06 2.598E-06 2.598E-06
IC 3.187E-04 3.187E-04 1.958E-04 1.958E-04 2.598E-04 2.598E-04
VBE 7.446E-01 7.446E-01 7.320E-01 7.320E-01 7.394E-01 7.394E-01
VCE 1.476E+00 1.476E+00 1.471E+00 1.471E+00 7.394E-01 7.394E-01
VBC -7.320E-01 -7.320E-01 -7.394E-01 -7.394E-01 0. 0.
VS -4.260E+00 -4.260E+00 -5.000E+00 -5.000E+00 -5.000E+00 -5.000E+00
POWER 4.730E-04 4.730E-04 2.895E-04 2.895E-04 1.940E-04 1.940E-04
BETAD 1.000E+02 1.000E+02 1.000E+02 1.000E+02 1.000E+02 1.000E+02
GM 1.232E-02 1.232E-02 7.569E-03 7.569E-03 1.005E-02 1.005E-02
RPI 8.115E+03 8.115E+03 1.321E+04 1.321E+04 9.953E+03 9.953E+03
RX 0. 0. 0. 0. 0. 0.
RO 7.320E+15 7.320E+15 7.393E+15 7.393E+15 2.586E+14 2.586E+14
BETAAC 9.999E+01 9.999E+01 9.999E+01 9.999E+01 9.999E+01 9.999E+01
FT 1.961E+12 1.961E+12 1.204E+12 1.204E+12 1.599E+12 1.599E+12
ELEMENT 0:Q7 0:Q8 0:Q9 0:Q10 0:Q11
MODEL 0:M 0:M 0:M 0:M 0:M
IB 3.219E-06 3.219E-06 1.945E-06 1.945E-06 1.945E-06
IC 3.219E-04 3.219E-04 1.945E-04 1.945E-04 1.945E-04
VBE 7.449E-01 7.449E-01 7.319E-01 7.319E-01 7.319E-01
VCE 2.458E+00 2.458E+00 3.528E+00 3.528E+00 7.319E-01
VBC -1.714E+00 -1.714E+00 -2.796E+00 -2.796E+00 0.
VS -2.784E+00 -2.784E+00 -3.528E+00 -3.528E+00 -7.319E-01
POWER 7.939E-04 7.939E-04 6.879E-04 6.879E-04 1.438E-04
BETAD 1.000E+02 1.000E+02 1.000E+02 1.000E+02 1.000E+02
GM 1.245E-02 1.245E-02 7.522E-03 7.522E-03 7.522E-03
RPI 8.035E+03 8.035E+03 1.329E+04 1.329E+04 1.329E+04
RX 0. 0. 0. 0. 0.
RO 1.714E+16 1.714E+16 2.796E+16 2.796E+16 2.586E+14
BETAAC 9.999E+01 9.999E+01 9.999E+01 9.999E+01 9.999E+01
FT 1.980E+12 1.980E+12 1.197E+12 1.197E+12 1.197E+12

***** TRANSIENT ANALYSIS TNOH= 27.000 TEMP= 27.000
TIME V(6,5)
(A) 1 -1.000E-00 -5.000E-01 0. 5.000E-01 1.000E-00
0. 0.
5.000E-05 -2.79E-02 + + + + + + + + + +
1.000E-05 -1.81E-01 + + + + A + + + + +
1.500E-05 -3.34E-01 + + + + A + + + + +
2.000E-05 -4.88E-01 + + A + + + + + + + +

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2.500E-05 -4.68E-01 + + + A + + + + + + + +
3.000E-05 -3.07E-01 + + + A + + + + + + + +
3.500E-05 -1.46E-01 + + + + A + + + + + + + +
4.000E-05 1.50E-02 + + + + A + + + + + + + +
4.500E-05 1.76E-01 + + + + + A + + + + + + + +
5.000E-05 3.37E-01 + + + + + A + + + + + + + +
5.500E-05 4.98E-01 + + + + + A + + + + + + + +
6.000E-05 4.85E-01 + + + + + A + + + + + + + +
6.500E-05 3.24E-01 + + + + + A + + + + + + + +
7.000E-05 1.63E-01 + + + + + A + + + + + + + +
7.500E-05 2.04E-03 + + + + + A + + + + + + + +
8.000E-05 -1.59E-01 + + + + + A + + + + + + + +
8.500E-05 -3.20E-01 + + + + + A + + + + + + + +
9.000E-05 -4.81E-01 + + + + + A + + + + + + + +
9.500E-05 -5.05E-01 + + + + + A + + + + + + + +
1.000E-04 -3.44E-01 + + + + + A + + + + + + + +
1.050E-04 -1.83E-01 + + + + + A + + + + + + + +
1.100E-04 -2.22E-02 + + + + + A + + + + + + + +
1.150E-04 1.39E-01 + + + + + A + + + + + + + +
1.200E-04 3.00E-01 + + + + + A + + + + + + + +
1.250E-04 4.61E-01 + + + + + A + + + + + + + +
1.300E-04 5.25E-01 + + + + + A + + + + + + + +
1.350E-04 3.64E-01 + + + + + A + + + + + + + +
1.400E-04 2.04E-01 + + + + + A + + + + + + + +
1.450E-04 4.26E-02 + + + + + A + + + + + + + +
1.500E-04 -1.18E-01 + + + + + A + + + + + + + +
1.550E-04 -2.79E-01 + + + + + A + + + + + + + +
1.600E-04 -4.40E-01 + + + + + A + + + + + + + +
1.650E-04 -5.46E-01 + + + + + A + + + + + + + +
1.700E-04 -3.85E-01 + + + + + A + + + + + + + +
1.750E-04 -2.24E-01 + + + + + A + + + + + + + +
1.800E-04 -6.33E-02 + + + + + A + + + + + + + +
1.850E-04 9.77E-02 + + + + + A + + + + + + + +
1.900E-04 2.59E-01 + + + + + A + + + + + + + +
1.950E-04 4.20E-01 + + + + + A + + + + + + + +
2.000E-04 5.67E-01 + + + + + A + + + + + + + +
2.050E-04 4.06E-01 + + + + + A + + + + + + + +
2.100E-04 2.45E-01 + + + + + A + + + + + + + +
2.150E-04 8.37E-02 + + + + + A + + + + + + + +
2.200E-04 -7.72E-02 + + + + + A + + + + + + + +
2.250E-04 -2.38E-01 + + + + + A + + + + + + + +
2.300E-04 -3.99E-01 + + + + + A + + + + + + + +
2.350E-04 -5.60E-01 + + + + + A + + + + + + + +
2.400E-04 -4.26E-01 + + + + + A + + + + + + + +
2.450E-04 -2.65E-01 + + + + + A + + + + + + + +
2.500E-04 -1.04E-01 + + + + + A + + + + + + + +
2.550E-04 5.65E-02 + + + + + A + + + + + + + +
2.600E-04 2.17E-01 + + + + + A + + + + + + + +
2.650E-04 3.74E-01 + + + + + A + + + + + + + +
2.700E-04 5.32E-01 + + + + + A + + + + + + + +
2.750E-04 4.06E-01 + + + + + A + + + + + + + +
2.800E-04 2.45E-01 + + + + + A + + + + + + + +
2.850E-04 8.43E-02 + + + + + A + + + + + + + +
2.900E-04 -7.66E-02 + + + + + A + + + + + + + +
2.950E-04 -2.38E-01 + + + + + A + + + + + + + +
3.000E-04 -3.99E-01 + + + + + A + + + + + + + +
3.050E-04 -5.59E-01 + + + + + A + + + + + + + +
3.100E-04 -4.27E-01 + + + + + A + + + + + + + +
3.150E-04 -2.66E-01 + + + + + A + + + + + + + +
3.200E-04 -1.05E-01 + + + + + A + + + + + + + +
3.250E-04 5.63E-02 + + + + + A + + + + + + + +
3.300E-04 2.17E-01 + + + + + A + + + + + + + +
3.350E-04 3.78E-01 + + + + + A + + + + + + + +
3.400E-04 5.39E-01 + + + + + A + + + + + + + +
3.450E-04 4.47E-01 + + + + + A + + + + + + + +
3.500E-04 2.86E-01 + + + + + A + + + + + + + +
3.550E-04 1.25E-01 + + + + + A + + + + + + + +
3.600E-04 -3.57E-02 + + + + + A + + + + + + + +
3.650E-04 -1.96E-01 + + + + + A + + + + + + + +
3.700E-04 -3.54E-01 + + + + + A + + + + + + + +
3.750E-04 -5.11E-01 + + + + + A + + + + + + + +
3.800E-04 -4.28E-01 + + + + + A + + + + + + + +
3.850E-04 -2.67E-01 + + + + + A + + + + + + + +
3.900E-04 -1.06E-01 + + + + + A + + + + + + + +
3.950E-04 5.47E-02 + + + + + A + + + + + + + +
4.000E-04 2.16E-01 + + + + + A + + + + + + + +
4.050E-04 3.77E-01 + + + + + A + + + + + + + +
4.100E-04 5.37E-01 + + + + + A + + + + + + + +
4.150E-04 4.49E-01 + + + + + A + + + + + + + +
4.200E-04 2.88E-01 + + + + + A + + + + + + + +
4.250E-04 1.27E-01 + + + + + A + + + + + + + +
4.300E-04 -3.38E-02 + + + + + A + + + + + + + +
4.350E-04 -1.95E-01 + + + + + A + + + + + + + +
4.400E-04 -3.56E-01 + + + + + A + + + + + + + +
4.450E-04 -5.17E-01 + + + + + A + + + + + + + +
4.500E-04 -4.70E-01 + + + + + A + + + + + + + +
4.550E-04 -3.09E-01 + + + + + A + + + + + + + +
4.600E-04 -1.48E-01 + + + + + A + + + + + + + +
4.650E-04 1.32E-02 + + + + + A + + + + + + + +
4.700E-04 1.74E-01 + + + + + A + + + + + + + +
4.750E-04 3.32E-01 + + + + + A + + + + + + + +
4.800E-04 4.89E-01 + + + + + A + + + + + + + +
4.850E-04 4.50E-01 + + + + + A + + + + + + + +
4.900E-04 2.89E-01 + + + + + A + + + + + + + +
4.950E-04 1.28E-01 + + + + + A + + + + + + + +
5.000E-04 -3.30E-02 + + + + + A + + + + + + + +

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10-12

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*****
* VI = BIAS + 100MV = 1.17V
* EXPECTED OSCILLATION FREQUENCY = 13.3 KHZ
* PERIOD = 75 US
* ACTUAL OSCILLATION FREQUENCY = 18.2 KHZ
* PERIOD = 55 US
*****
* VOLTAGE CONTROLLED OSCILLATOR
VCC 1 0 5V
Q1 7 10 5 N
Q2 8 9 6 N
Q3 1 7 9 N
Q4 1 8 10 N
Q5 1 1 7 N
Q6 1 1 8 N
Q7 5 2 3 N
Q8 6 2 4 N
R1 1 7 12.7K
R2 1 8 12.7K
R3 3 0 1K
R4 4 0 1K
Q9 10 13 0 N
Q10 9 13 0 N
Q11 13 13 0 N
R5 1 13 21.3K
* ADDED A SMALL CAPACITOR BETWEEN NODES 7,8
CAP 5 61 0.01UF
VI 2 0 1.17V
* ADDED A SERIES PWL VOLTAGE TO LOAD CAP TO SET IC
WKICK 61 6 PWL 0 100M 1US 100M 1.01US 0
CX1 7 8 0.01MF
.MODEL N BPN BF=100 IS=1E-16
.PLOT V(6,5)
.TRAN 5US 500US
.OPTIONS NOPAGE NOMOD LIMPTS=700
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

```

+0:1 = 5.000E+00 0:2 = 1.170E+00 0:3 = 4.186E-01
+0:4 = 4.186E-01 0:5 = 2.769E+00 0:6 = 2.769E+00
+0:7 = 4.252E+00 0:8 = 4.252E+00 0:9 = 3.520E+00
+0:10 = 3.520E+00 0:13 = 7.319E-01 0:61 = 2.869E+00

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**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	0:Q1	0:Q2	0:Q3	0:Q4	0:Q5	0:Q6
MODEL	0:N	0:N	0:N	0:N	0:N	0:N
IB	4.103E-06	4.103E-06	1.967E-06	1.967E-06	3.500E-06	3.500E-06
IC	4.103E-04	4.103E-04	1.967E-04	1.967E-04	3.500E-04	3.500E-04
VBE	7.512E-01	7.512E-01	7.321E-01	7.321E-01	7.471E-01	7.471E-01
VCE	1.483E+00	1.483E+00	1.479E+00	1.479E+00	7.471E-01	7.471E-01
VBC	-7.321E-01	-7.321E-01	-7.471E-01	-7.471E-01	0.	0.
VS	-4.252E+00	-4.252E+00	-5.000E+00	-5.000E+00	-5.000E+00	-5.000E+00
POWER	6.117E-04	6.117E-04	2.924E-04	2.924E-04	2.641E-04	2.641E-04
BETAD	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02
GM	1.586E-02	1.586E-02	7.604E-03	7.604E-03	1.353E-02	1.353E-02
RPI	6.303E+03	6.303E+03	1.315E+04	1.315E+04	7.390E+03	7.390E+03
RX	0.	0.	0.	0.	0.	0.
RO	7.321E+15	7.321E+15	7.470E+15	7.470E+15	2.586E+14	2.586E+14
BETAC	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01
FT	2.524E+12	2.524E+12	1.210E+12	1.210E+12	2.153E+12	2.153E+12

ELEMENT	0:Q7	0:Q8	0:Q9	0:Q10	0:Q11
MODEL	0:N	0:N	0:N	0:N	0:N
IB	4.144E-06	4.144E-06	1.945E-06	1.945E-06	1.945E-06
IC	4.144E-04	4.144E-04	1.945E-04	1.945E-04	1.945E-04
VBE	7.514E-01	7.514E-01	7.319E-01	7.319E-01	7.319E-01
VCE	2.351E+00	2.351E+00	3.520E+00	3.520E+00	7.319E-01
VBC	-1.599E+00	-1.599E+00	-2.788E+00	-2.788E+00	0.
VS	-2.769E+00	-2.769E+00	-3.520E+00	-3.520E+00	-7.319E-01
POWER	9.775E-04	9.775E-04	6.864E-04	6.864E-04	1.438E-04
BETAD	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02
GM	1.602E-02	1.602E-02	7.522E-03	7.522E-03	7.522E-03
RPI	6.240E+03	6.240E+03	1.329E+04	1.329E+04	1.329E+04
RX	0.	0.	0.	0.	0.
RO	1.599E+16	1.599E+16	2.788E+16	2.788E+16	2.586E+14
BETAC	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01
FT	2.550E+12	2.550E+12	1.197E+12	1.197E+12	1.197E+12

***** TRANSIENT ANALYSIS THOM= 27.000 TEMP= 27.000

TIME	V(6,5)
0	-1.000E-00
5.000E-06	-6.52E-02
1.000E-05	-2.68E-01
1.500E-05	-4.70E-01
2.000E-05	-4.53E-01
2.500E-05	-2.48E-01
3.000E-05	-4.10E-02
3.500E-05	1.66E-01
4.000E-05	3.73E-01
4.500E-05	5.66E-01

5.000E-05	3.59E-01
5.500E-05	1.52E-01
6.000E-05	-5.56E-02
6.500E-05	-2.63E-01
7.000E-05	-4.70E-01
7.500E-05	-4.71E-01
8.000E-05	-2.63E-01
8.500E-05	-5.61E-02
9.000E-05	1.51E-01
9.500E-05	3.58E-01
1.000E-04	5.65E-01
1.050E-04	3.76E-01
1.100E-04	1.69E-01
1.150E-04	-3.83E-02
1.200E-04	-2.45E-01
1.250E-04	-4.53E-01
1.300E-04	-4.90E-01
1.350E-04	-2.83E-01
1.400E-04	-7.54E-02
1.450E-04	1.32E-01
1.500E-04	3.39E-01
1.550E-04	5.46E-01
1.600E-04	3.96E-01
1.650E-04	1.89E-01
1.700E-04	-1.81E-02
1.750E-04	-2.25E-01
1.800E-04	-4.32E-01
1.850E-04	-5.10E-01
1.900E-04	-3.03E-01
1.950E-04	-9.57E-02
2.000E-04	1.12E-01
2.050E-04	3.19E-01
2.100E-04	5.26E-01
2.150E-04	4.17E-01
2.200E-04	2.09E-01
2.250E-04	2.25E-03
2.300E-04	-2.05E-01
2.350E-04	-4.12E-01
2.400E-04	-5.30E-01
2.450E-04	-3.23E-01
2.500E-04	-1.16E-01
2.550E-04	9.13E-02
2.600E-04	2.99E-01
2.650E-04	5.06E-01
2.700E-04	4.37E-01
2.750E-04	2.30E-01
2.800E-04	2.24E-02
2.850E-04	-1.85E-01
2.900E-04	-3.92E-01
2.950E-04	-5.51E-01
3.000E-04	-3.43E-01
3.050E-04	-1.36E-01
3.100E-04	7.11E-02
3.150E-04	2.78E-01
3.200E-04	4.85E-01
3.250E-04	4.57E-01
3.300E-04	2.50E-01
3.350E-04	4.27E-02
3.400E-04	-1.65E-01
3.450E-04	-3.72E-01
3.500E-04	-5.73E-01
3.550E-04	-3.66E-01
3.600E-04	-1.58E-01
3.650E-04	4.89E-02
3.700E-04	2.56E-01
3.750E-04	4.63E-01
3.800E-04	4.79E-01
3.850E-04	2.72E-01
3.900E-04	6.44E-02
3.950E-04	-1.43E-01
4.000E-04	-3.50E-01
4.050E-04	-5.57E-01
4.100E-04	-3.85E-01
4.150E-04	-1.78E-01
4.200E-04	2.94E-02
4.250E-04	2.37E-01
4.300E-04	4.44E-01
4.350E-04	4.99E-01
4.400E-04	2.91E-01
4.450E-04	8.41E-02
4.500E-04	-1.23E-01
4.550E-04	-3.30E-01
4.600E-04	-5.37E-01
4.650E-04	-4.05E-01
4.700E-04	-1.98E-01
4.750E-04	9.58E-02
4.800E-04	2.17E-01
4.850E-04	4.24E-01
4.900E-04	5.19E-01
4.950E-04	3.11E-01
5.000E-04	1.04E-01

10-13

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*****
* VI = BIAS -100MV = 0.97V
* EXPECTED OSCILLATION FREQUENCY = 6.65 KHZ
* PERIOD = 150 US
* ACTUAL OSCILLATION FREQUENCY = 10 KHZ
* PERIOD = 100 US
*****
* VOLTAGE CONTROLLED OSCILLATOR
VCC 1 0 5V
Q1 7 10 5 N
Q2 8 9 6 N
Q3 1 7 9 N
Q4 1 8 10 N
Q5 1 1 7 N
Q6 1 1 8 N
Q7 5 2 3 N
Q8 6 2 4 N
R1 1 7 12.7K
R2 1 8 12.7K
R3 3 0 1K
R4 4 0 1K
Q9 10 13 0 N
Q10 9 13 0 N
Q11 13 13 0 N
R5 1 13 21.3K
* ADDED A SMALL CAPACITOR BETWEEN NODES 7,8
CAP 5 61 0.01UF
VI 2 0 0.97V
* ADDED A SERIES PWL VOLTAGE TO LOAD CAP TO SET IC
VKICK 61 6 PWL 0 100M 1US 100M 1.01US 0
CX1 7 8 0.01NF
.MODEL N NPN BF=100 IS=1E-16
.PLOT V(6,5)
.TRAN 5US 500US
.OPTIONS NOPAGE NOMOD LIMPTS=700
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

***** OPERATING POINT INFORMATION          TWOM= 27.000 TEMP= 27.000

+0:1      = 5.000E+00 0:2      = 9.700E-01 0:3      = 2.337E-01
+0:4      = 2.337E-01 0:5      = 2.803E+00 0:6      = 2.803E+00
+0:7      = 4.271E+00 0:8      = 4.271E+00 0:9      = 3.539E+00
+0:10     = 3.539E+00 0:13     = 7.319E-01 0:61     = 2.903E+00

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT 0:Q1      0:Q2      0:Q3      0:Q4      0:Q5      0:Q6
MODEL   0:N      0:N      0:N      0:N      0:N      0:N
IB       2.290E-06 2.290E-06 1.949E-06 1.949E-06 1.719E-06 1.719E-06
IC       2.290E-04 2.290E-04 1.949E-04 1.949E-04 1.719E-04 1.719E-04
VBE      7.361E-01 7.361E-01 7.319E-01 7.319E-01 7.287E-01 7.287E-01
VCE      1.468E+00 1.468E+00 1.460E+00 1.460E+00 7.287E-01 7.287E-01
VBC      -7.319E-01 -7.319E-01 -7.287E-01 -7.287E-01 0.      0.
VS       -4.271E+00 -4.271E+00 -5.000E+00 -5.000E+00 -5.000E+00 -5.000E+00
POWER    3.379E-04 3.379E-04 2.861E-04 2.861E-04 1.265E-04 1.265E-04
BETAD    1.000E+02 1.000E+02 1.000E+02 1.000E+02 1.000E+02 1.000E+02
GM        8.856E-03 8.856E-03 7.535E-03 7.535E-03 6.646E-03 6.646E-03
RPI       1.129E+04 1.129E+04 1.327E+04 1.327E+04 1.504E+04 1.504E+04
RX         0.      0.      0.      0.      0.      0.
RO        7.319E+15 7.319E+15 7.286E+15 7.286E+15 2.586E+14 2.586E+14
BETAAC    9.999E+01 9.999E+01 9.999E+01 9.999E+01 9.999E+01 9.999E+01
FT        1.409E+12 1.409E+12 1.199E+12 1.199E+12 1.057E+12 1.057E+12

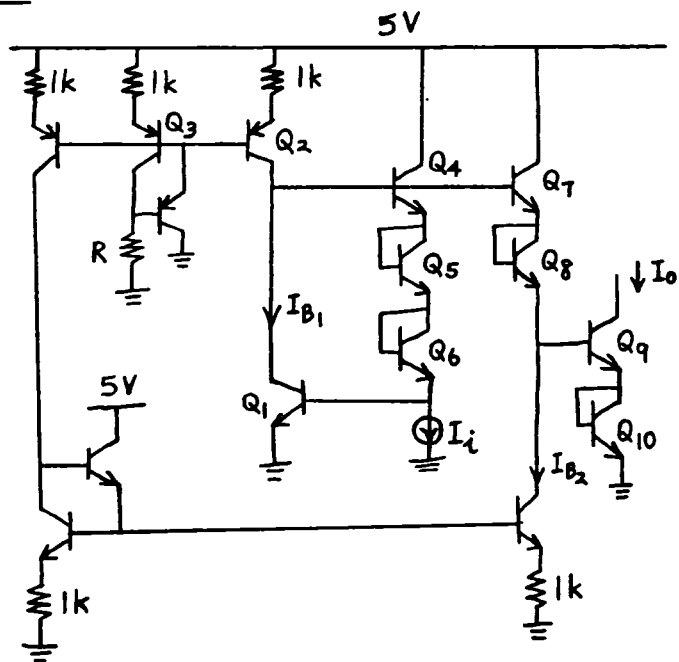
ELEMENT 0:Q7      0:Q8      0:Q9      0:Q10     0:Q11
MODEL   0:N      0:N      0:N      0:N      0:N
IB       2.313E-06 2.313E-06 1.945E-06 1.945E-06 1.945E-06
IC       2.313E-04 2.313E-04 1.945E-04 1.945E-04 1.945E-04
VBE      7.363E-01 7.363E-01 7.319E-01 7.319E-01 7.319E-01
VCE      2.569E+00 2.569E+00 3.539E+00 3.539E+00 7.319E-01
VBC      -1.833E+00 -1.833E+00 -2.807E+00 -2.807E+00 0.
VS       -2.803E+00 -2.803E+00 -3.539E+00 -3.539E+00 -7.319E-01
POWER    5.962E-04 5.962E-04 6.900E-04 6.900E-04 1.438E-04
BETAD    1.000E+02 1.000E+02 1.000E+02 1.000E+02 1.000E+02
GM        8.944E-03 8.944E-03 7.522E-03 7.522E-03 7.522E-03
RPI       1.118E+04 1.118E+04 1.329E+04 1.329E+04 1.329E+04
RX         0.      0.      0.      0.      0.
RO        1.833E+16 1.833E+16 2.807E+16 2.807E+16 2.586E+14
BETAAC    9.999E+01 9.999E+01 9.999E+01 9.999E+01 9.999E+01
FT        1.423E+12 1.423E+12 1.197E+12 1.197E+12 1.197E+12

***** TRANSIENT ANALYSIS          TWOM= 27.000 TEMP= 27.000

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2.000E-05 -3.40E-01 + + + + A + + + +
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3.000E-05 -5.59E-01 + + + + A + + + +
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15.70E-04 -8.42E-01 + + + + A + + + +
15.75E-04 -8.59E-01 + + + + A + + + +
15.80E-04 -8.77E-01 + + + + A + + + +
15.85E-04 -8.94E-01 + + + + A + + + +
15.90E-04 -9.12E-01 + + + + A + + + +
15.95E-04 -9.29E-01 + + + + A + + + +
16.00E-04 -9.47E-01 + + + + A + + + +
16.05E-04 -9.64E-01 + + + + A + + + +
16.10E-04 -9.82E-01 + + + + A + + + +
16.15E-04 -9.99E-01 + + + + A + + + +
16.20E-04 -1.07E-01 + + + + A + + + +
16.25E-04 -1.25E-01 + + + + A + + + +
16.30E-04 -1.42E-01 + + + + A + + + +
16.35E-04 -1.59E-01 + + + + A + + + +
16.40E-04 -1.77E-01 + + + + A + + + +
16.45E-04 -1.94E-01 + + + + A + + + +
16.50E-04 -2.12E-01 + + + + A + + + +
16.55E-04 -2.29E-01 + + + + A + + + +
16.60E-04 -2.47E-01 + + + + A + + + +
16.65E-04 -2.64E-01 + + + + A + + + +
16.70E-04 -2.82E-01 + + + + A + + + +
16.75E-04 -2.99E-01 + + + + A + + + +
16.80E-04 -3.17E-01 + + + + A + + + +
16.85E-04 -3.34E-01 + + + + A + + + +
16.90E-04 -3.52E-01 + + + + A + + + +
16.95E-04 -3.69E-01 + + + + A + + + +
17.00E-04 -3.87E-01 + + + + A + + + +
17.05E-04 -4.04E-01 + + + + A + + + +
17.10E-04 -4.22E-01 + + + + A + + + +
17.15E-04 -4.39E-01 + + + + A + + + +
17.20E-04 -4.57E-01 + + + + A + + + +
17.25E-04 -4.74E-01 + + + + A + + + +
17.30E-04 -4.92E-01 + + + + A + + + +
17.35E-04 -5.09E-01 + + + + A + + + +
17.40E-04 -5.27E-01 + + + + A + + + +
17.45E-04 -5.44E-01 + + + + A + + + +
17.50E-04 -5.62E-01 + + + + A + + + +
17.55E-04 -5.79E-01 + + + + A + + + +
17.60E-04 -5.97E-01 + + + + A + + + +
17.65E-04 -6.14E-01 + + + + A + + + +

```

10-14



$$\frac{I_{B1} I_i^3}{I_s^4} = \frac{I_{B2}^2 I_o^2}{I_s^4}$$

$$I_o = \frac{\sqrt{I_{B1}}}{I_{B2}} I_i^{3/2}$$

$$100 \mu = \frac{\sqrt{I_{B1}}}{I_{B2}} 100 \mu^{\frac{3}{2}}$$

$$100 = \frac{\sqrt{I_{B1}}}{I_{B2}}$$

set $I_{B2} = 100\mu$

then $I_{B1} = 100\mu$

$$R = \frac{5 - 2V_{BE} - 100m}{100\mu} = 33.4k$$

$$V_{BE} = V_T \ln \frac{I_C}{I_S} = V_T \ln \frac{100 \mu}{10^{-17}} = 0.778V$$

$$I_0 = K I_i^{\frac{3}{2}} = 100 I_i^{\frac{3}{2}}$$

10-15

NONLINEAR FUNCTION SYNTHESIS

```

VCC 1 0 5V
Q1 5 2 0 N
Q2 5 14 18 P
RQ2 18 1 1K
Q3 15 14 17 P
RQ3 17 1 1K
Q12 13 14 16 P
RQ12 16 1 1K
Q11 0 15 14 P
RBIAS 15 0 33.4K
Q4 1 5 4 N
Q5 4 4 3 N
Q6 3 3 2 N
II 2 0 100UA
Q7 1 5 6 N
Q8 6 6 7 N
Q15 7 10 11 N
RQ15 11 0 1K
Q9 8 7 9 N
Q10 9 9 0 N
Q13 13 10 12 N
RQ13 12 0 1K
Q14 1 13 10 N
VZVBE 20 0 1.56V
VDUMMY 20 8 0V
.MODEL N NPN BF=100 IS=1E-17
.MODEL P PNP BF=100 IS=1E-17
.DC II 0 5000 100
.PLOT DC I(VDUMMY)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** DC TRANSFER CURVES

TNOM= 27.000 TEMP= 27.000

AMPS (A)	I(VDUMMY) -5.000E-04	0.	5.000E-04	1.000E-03	1.500E-03
0.	1.00E-07	+	+	+	+
1.000E-05	3.57E-06	+	A	+	+
2.000E-05	9.39E-06	+	A	+	+
3.000E-05	1.68E-05	+	A	+	+
4.000E-05	2.55E-05	+	A	+	+
5.000E-05	3.54E-05	+	A	+	+
6.000E-05	4.62E-05	+	A	+	+
7.000E-05	5.79E-05	+	A	+	+
8.000E-05	7.04E-05	+	A	+	+
9.000E-05	8.37E-05	+	A	+	+
1.000E-04	9.77E-05	+	A	+	+
1.100E-04	1.12E-04	+	A	+	+
1.200E-04	1.28E-04	+	A	+	+
1.300E-04	1.43E-04	+	A	+	+
1.400E-04	1.60E-04	+	A	+	+
1.500E-04	1.77E-04	+	A	+	+
1.600E-04	1.94E-04	+	A	+	+
1.700E-04	2.12E-04	+	A	+	+
1.800E-04	2.30E-04	+	A	+	+
1.900E-04	2.49E-04	+	A	+	+
2.000E-04	2.68E-04	+	A	+	+
2.100E-04	2.88E-04	+	A	+	+
2.200E-04	3.08E-04	+	A	+	+
2.300E-04	3.28E-04	+	A	+	+
2.400E-04	3.49E-04	+	A	+	+
2.500E-04	3.70E-04	+	A	+	+
2.600E-04	3.91E-04	+	A	+	+
2.700E-04	4.13E-04	+	A	+	+
2.800E-04	4.35E-04	+	A	+	+
2.900E-04	4.57E-04	+	A	+	+
3.000E-04	4.80E-04	+	A	+	+
3.100E-04	5.03E-04	+	A	+	+
3.200E-04	5.26E-04	+	A	+	+
3.300E-04	5.49E-04	+	A	+	+
3.400E-04	5.72E-04	+	A	+	+
3.500E-04	5.96E-04	+	A	+	+
3.600E-04	6.20E-04	+	A	+	+
3.700E-04	6.44E-04	+	A	+	+
3.800E-04	6.69E-04	+	A	+	+
3.900E-04	6.93E-04	+	A	+	+
4.000E-04	7.18E-04	+	A	+	+
4.100E-04	7.43E-04	+	A	+	+
4.200E-04	7.68E-04	+	A	+	+
4.300E-04	7.93E-04	+	A	+	+
4.400E-04	8.19E-04	+	A	+	+
4.500E-04	8.44E-04	+	A	+	+
4.600E-04	8.70E-04	+	A	+	+
4.700E-04	8.96E-04	+	A	+	+
4.800E-04	9.22E-04	+	A	+	+
4.900E-04	9.48E-04	+	A	+	+
5.000E-04	9.75E-04	+	A	+	+

***** OPERATING POINT INFORMATION TNOM= 27.000 TEMP= 27.000

```

+0:1 = 5.000E+00 0:2 = 7.744E-01 0:3 = 1.548E+00
+0:4 = 2.322E+00 0:5 = 3.097E+00 0:6 = 2.322E+00
+0:7 = 1.547E+00 0:8 = 1.560E+00 0:9 = 7.736E-01
+0:10 = 8.788E-01 0:11 = 1.039E-01 0:12 = 1.039E-01
+0:13 = 1.552E+00 0:14 = 4.121E+00 0:15 = 3.437E+00
+0:16 = 4.896E+00 0:17 = 4.896E+00 0:18 = 4.896E+00
+0:20 = 1.560E+00

```

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	0:Q1	0:Q2	0:Q3	0:Q12	0:Q11	0:Q4
MODEL	0:N	0:P	0:P	0:P	0:P	0:N
IB	1.009E-06	-1.029E-06	-1.029E-06	-1.029E-06	-3.056E-08	1.000E-06
IC	1.009E-04	-1.029E-04	-1.029E-04	-1.029E-04	-3.056E-06	1.000E-04
VBE	7.744E-01	-7.749E-01	-7.749E-01	-7.749E-01	-6.840E-01	7.742E-01
VCE	3.097E+00	-1.799E+00	-1.458E+00	-3.343E+00	-4.121E+00	2.677E+00
VBC	-2.322E+00	1.024E+00	6.840E-01	2.568E+00	3.437E+00	-1.902E+00
VS	-3.097E+00	-4.121E+00	-4.121E+00	-4.121E+00	-3.437E+00	-5.000E+00
POWER	3.131E-04	1.859E-04	1.509E-04	3.448E-04	1.261E-05	2.685E-04
BETAD	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02
GM	3.899E-03	3.978E-03	3.978E-03	3.978E-03	1.181E-04	3.867E-03
RPI	2.564E+04	2.514E+04	2.514E+04	2.514E+04	8.464E+05	2.586E+04
RX	0.	0.	0.	0.	0.	0.
RO	2.322E+17	1.024E+17	6.839E+16	2.568E+17	3.437E+17	1.902E+17
CPI	0.	0.	0.	0.	0.	0.
CMU	0.	0.	0.	0.	0.	0.
CRX	0.	0.	0.	0.	0.	0.
CCS	0.	0.	0.	0.	0.	0.
BETAAC	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01
FT	6.205E+11	6.330E+11	6.330E+11	6.330E+11	1.880E+10	6.154E+11

ELEMENT	0:Q5	0:Q6	0:Q7	0:Q8	0:Q15	0:Q9
MODEL	0:N	0:N	0:N	0:N	0:N	0:N
IB	1.000E-06	1.000E-06	1.028E-06	1.028E-06	1.029E-06	9.769E-07
IC	1.000E-04	1.000E-04	1.028E-04	1.028E-04	1.029E-04	9.769E-05
VBE	7.742E-01	7.742E-01	7.749E-01	7.749E-01	7.749E-01	7.736E-01
VCE	7.742E-01	7.742E-01	2.677E+00	7.749E-01	1.443E+00	7.864E-01
VBC	0.	0.	-1.902E+00	0.	-6.684E-01	-1.279E-02
VS	-2.322E+00	-1.548E+00	-5.000E+00	-2.322E+00	-1.547E+00	-1.560E+00
POWER	7.820E-05	7.820E-05	2.761E-04	8.046E-05	1.493E-04	7.758E-05
BETAD	1.000E+02	9.999E+01	1.000E+02	1.000E+02	1.000E+02	1.000E+02
GM	3.867E-03	3.867E-03	3.975E-03	3.975E-03	3.977E-03	3.777E-03
RPI	2.586E+04	2.586E+04	2.515E+04	2.515E+04	2.514E+04	2.647E+04
RX	0.	0.	0.	0.	0.	0.
RO	2.586E+15	2.586E+15	1.902E+17	2.586E+15	6.683E+16	4.240E+15
CPI	0.	0.	0.	0.	0.	0.
CMU	0.	0.	0.	0.	0.	0.
CRX	0.	0.	0.	0.	0.	0.
CCS	0.	0.	0.	0.	0.	0.
BETAAC	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01
FT	6.154E+11	6.154E+11	6.326E+11	6.326E+11	6.329E+11	6.011E+11

ELEMENT	0:Q10	0:Q13	0:Q14
MODEL	0:N	0:N	0:N
IB	9.769E-07	1.029E-06	2.037E-08
IC	9.769E-05	1.029E-04	2.037E-06
VBE	7.736E-01	7.749E-01	6.735E-01
VCE	7.736E-01	1.448E+00	4.121E+00
VBC	0.	-6.735E-01	-3.447E+00
VS	-7.736E-01	-1.552E+00	-5.000E+00
POWER	7.633E-05	1.498E-04	8.408E-06
BETAD	1.000E+02	1.000E+02	1.000E+02
GM	3.777E-03	3.977E-03	7.875E-05
RPI	2.647E+04	2.514E+04	1.269E+06
RX	0.	0.	0.
RO	2.586E+15	6.735E+16	3.447E+17
CPI	0.	0.	0.
CMU	0.	0.	0.
CRX	0.	0.	0.
CCS	0.	0.	0.
BETAAC	9.999E+01	9.999E+01	9.999E+01
FT	6.011E+11	6.329E+11	1.253E+10

II (UA)	100*II*1.5 (UA)	IO (UA)	ERROR (%)
100	100	97.7	2.3
200	283	268	5.1
300	520	480	7.7
400	800	718	10.2

10-16

NONLINEAR FUNCTION SYNTHESIS, ADD RB AND RE

```
VCC 1 0 5V
Q1 5 2 0 N
Q2 5 14 18 P
RQ2 18 1 1K
Q3 15 14 17 P
RQ3 17 1 1K
Q12 13 14 16 P
RQ12 16 1 1K
Q11 0 15 14 P
RBIAS 15 0 33.4K
Q4 1 5 4 N
Q5 4 4 3 N
Q6 3 3 2 N
II 2 0 100UA
Q7 1 5 6 N
Q8 6 6 7 N
Q15 7 10 11 N
RQ15 11 0 1K
Q9 8 7 9 N
Q10 9 9 0 N
Q13 13 10 12 N
RQ13 12 0 1K
Q14 1 13 10 N
VZVBE 20 0 1.56V
VDUMY 20 8 0V
.MODEL N NPN BF=100 IS=1E-17 RB=200 RE=2
.MODEL P PNP BF=100 IS=1E-17 RB=200 RE=2
.DC II 0 500U 10U
.PLOT DC I(VDUMY)
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END
```

***** DC TRANSFER CURVES THOM= 27.000 TEMP= 27.000

AMPS	I(VDUMY)				
(A)		0.	5.000E-04	1.000E-03	1.500E-03
0.	9.96E-08	A			
1.000E-05	3.55E-06	A			
2.000E-05	9.35E-06	A			
3.000E-05	1.68E-05	A			
4.000E-05	2.55E-05	A			
5.000E-05	3.51E-05	A			
6.000E-05	4.61E-05	A			
7.000E-05	5.79E-05	A			
8.000E-05	7.04E-05	A			
9.000E-05	8.37E-05	A			
1.000E-04	9.77E-05	A			
1.100E-04	1.12E-04	A			
1.200E-04	1.28E-04	A			
1.300E-04	1.43E-04	A			
1.400E-04	1.60E-04	A			
1.500E-04	1.77E-04	A			
1.600E-04	1.94E-04	A			
1.700E-04	2.12E-04	A			
1.800E-04	2.30E-04	A			
1.900E-04	2.49E-04	A			
2.000E-04	2.68E-04	A			
2.100E-04	2.87E-04	A			
2.200E-04	3.06E-04	A			
2.300E-04	3.26E-04	A			
2.400E-04	3.47E-04	A			
2.500E-04	3.67E-04	A			
2.600E-04	3.89E-04	A			
2.700E-04	4.09E-04	A			
2.800E-04	4.31E-04	A			
2.900E-04	4.52E-04	A			
3.000E-04	4.74E-04	A			
3.100E-04	4.96E-04	A			
3.200E-04	5.18E-04	A			
3.300E-04	5.40E-04	A			
3.400E-04	5.63E-04	A			
3.500E-04	5.86E-04	A			
3.600E-04	6.08E-04	A			
3.700E-04	6.31E-04	A			
3.800E-04	6.54E-04	A			
3.900E-04	6.78E-04	A			
4.000E-04	7.01E-04	A			
4.100E-04	7.24E-04	A			
4.200E-04	7.46E-04	A			
4.300E-04	7.72E-04	A			
4.400E-04	7.95E-04	A			
4.500E-04	8.19E-04	A			
4.600E-04	8.43E-04	A			
4.700E-04	8.67E-04	A			
4.800E-04	8.91E-04	A			
4.900E-04	9.15E-04	A			
5.000E-04	9.40E-04	A			

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	0:Q1	0:Q2	0:Q3	0:Q12	0:Q11	0:Q4
MODEL	0:N	0:P	0:P	0:P	0:P	0:N
IB	1.008E-06	-1.029E-06	-1.029E-06	-1.029E-06	-3.055E-08	1.000E-06
IC	1.008E-04	-1.029E-04	-1.029E-04	-1.029E-04	-3.055E-06	1.000E-04
VBE	7.748E-01	-7.754E-01	-7.754E-01	-7.754E-01	-6.840E-01	7.746E-01
VCE	3.098E+00	-1.797E+00	-1.459E+00	-3.343E+00	-4.120E+00	2.675E+00
VBC	-2.323E+00	1.022E+00	6.840E-01	2.568E+00	3.436E+00	-1.901E+00
VS	-3.098E+00	-4.121E+00	-4.121E+00	-4.121E+00	-3.436E+00	-5.000E+00
POWER	3.132E-04	1.857E-04	1.509E-04	3.447E-04	1.261E-05	2.684E-04
BETAD	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02
GM	3.899E-03	3.977E-03	3.977E-03	3.977E-03	1.181E-04	3.867E-03
RPI	2.564E+04	2.514E+04	2.514E+04	2.514E+04	8.465E+05	2.586E+04
RX	2.000E+02	2.000E+02	2.000E+02	2.000E+02	2.000E+02	2.000E+02
RO	2.324E+17	1.022E+17	6.842E+16	2.568E+17	3.436E+17	1.901E+17
CPI	0.	0.	0.	0.	0.	0.
CMU	0.	0.	0.	0.	0.	0.
CBX	0.	0.	0.	0.	0.	0.
CCS	0.	0.	0.	0.	0.	0.
BETAAC	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01
FT	6.205E+11	6.329E+11	6.329E+11	6.329E+11	1.880E+10	6.154E+11

ELEMENT	0:Q5	0:Q6	0:Q7	0:Q8	0:Q15	0:Q9
MODEL	0:N	0:N	0:N	0:N	0:N	0:N
IB	1.000E-06	1.000E-06	1.028E-06	1.028E-06	1.028E-06	9.770E-07
IC	1.000E-04	1.000E-04	1.028E-04	1.028E-04	1.028E-04	9.770E-05
VBE	7.746E-01	7.746E-01	7.753E-01	7.753E-01	7.753E-01	7.740E-01
VCE	7.746E-01	7.746E-01	2.676E+00	7.753E-01	1.444E+00	7.860E-01
VBC	0.	0.	-1.901E+00	0.	-6.688E-01	-1.200E-02
VS	-2.324E+00	-1.549E+00	-5.000E+00	-2.323E+00	-1.548E+00	-1.560E+00
POWER	7.824E-05	7.824E-05	2.759E-04	8.050E-05	1.493E-04	7.755E-05
BETAD	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02	1.000E+02
GM	3.867E-03	3.867E-03	3.974E-03	3.974E-03	3.976E-03	3.777E-03
RPI	2.586E+04	2.586E+04	2.516E+04	2.516E+04	2.514E+04	2.647E+04
RX	2.000E+02	2.000E+02	2.000E+02	2.000E+02	2.000E+02	2.000E+02
RO	2.606E+15	2.606E+15	1.901E+17	2.607E+15	6.689E+16	4.144E+15
CPI	0.	0.	0.	0.	0.	0.
CMU	0.	0.	0.	0.	0.	0.
CBX	0.	0.	0.	0.	0.	0.
CCS	0.	0.	0.	0.	0.	0.
BETAAC	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01	9.999E+01
FT	6.154E+11	6.154E+11	6.325E+11	6.325E+11	6.328E+11	6.011E+11

ELEMENT	0:Q10	0:Q13	0:Q14
MODEL	0:N	0:N	0:N
IB	9.770E-07	1.028E-06	2.037E-08
IC	9.770E-05	1.028E-04	2.037E-06
VBE	7.740E-01	7.753E-01	6.735E-01
VCE	7.740E-01	1.448E+00	4.120E+00
VBC	0.	-6.735E-01	-3.447E+00
VS	-7.740E-01	-1.552E+00	-5.000E+00
POWER	7.638E-05	1.498E-04	8.406E-06
BETAD	1.000E+02	1.000E+02	1.000E+02
GM	3.777E-03	3.976E-03	7.874E-05
RPI	2.647E+04	2.514E+04	1.270E+06
RX	2.000E+02	2.000E+02	2.000E+02
RO	2.606E+15	6.737E+16	3.447E+17
CPI	0.	0.	0.
CMU	0.	0.	0.
CBX	0.	0.	0.
CCS	0.	0.	0.
BETAAC	9.999E+01	9.999E+01	9.999E+01
FT	6.011E+11	6.328E+11	1.253E+10

II (UA)	100*II*1.5 (UA)	IO (UA)	ERROR (%)
100	100	97.7	2.3
200	283	268	5.1
300	520	474	8.9
400	800	701	12.4

10.15

10-17

$$I_{D1} = I_{D2} = I_{D3} = I_{D4} = 50 \mu A$$

$$I_{D5} = I_{D6} = I_{D7} = I_{D8} = 50 \mu A$$

$$I_{D9} = I_{D10} = 100 \mu A$$

$$I_D = \frac{\mu C_{ox}}{2} \frac{W}{L} (V_{GS} - V_t)^2$$

for m_1 thru m_8

$$50 \mu = \frac{60(20)}{2} (V_{GS} - V_t)^2 \mu$$

$$V_{GS} - V_t = 0.29 V$$

for m_9, m_{10}

$$100 \mu = \frac{60(20)}{2} (V_{GS} - V_t)^2 \mu$$

$$V_{GS} - V_t = 0.41 V$$

$$I_{D2} = |I_{D7}|$$

$$\frac{\mu_n C_{ox} (W)}{2 (L)_2} (V_{GS2} - V_{t2})^2 = \frac{\mu_p C_{ox} (W)}{2 (L)_7} (V_{GS7} - V_{t7})^2$$

$$V_{GS2} - V_{t2} = |V_{GS7}| - |V_{t7}|$$

$$\gamma = 0 \therefore V_{t2} = |V_{t7}|$$

$$V_{GS2} = |V_{GS7}|$$

 $\therefore m_2$ and m_7 share V_i equally

$$I_{D2} = \frac{\mu_n C_{ox} (W)}{2 (L)_2} \left(V_{GS \text{ bias}} + \frac{V_i}{2} - V_t \right)^2$$

$$I_{D3} = \frac{\mu_n C_{ox} (W)}{2 (L)_3} \left(V_{GS \text{ bias}} - \frac{V_i}{2} - V_t \right)^2$$

$$I_o = |I_{D10}| - 2I_1 = |I_{D9}| - 2I_1$$

$$= I_{D2} + I_{D3} - 2I_1$$

$$= \frac{\mu_n C_{ox} W}{2 L} \left[2(V_{GS \text{ bias}} - V_t)^2 + 2\left(\frac{V_i}{2}\right)^2 \right] - 2I_1$$

$$I_1 = \frac{\mu_n C_{ox} W}{2 L} (V_{GS \text{ bias}} - V_t)^2$$

$$\therefore I_o = \mu_n C_{ox} \frac{W}{L} \left(\frac{V_i^2}{4} \right)$$

$$= 300 \mu V_i^2$$

The above is true for m_2, m_3, m_6, m_7 all on.

$$|V_i| < 2(V_{GS} - V_t)$$

$$|V_i| < 2(0.29 V) = 0.58 V$$

10-18

CROSS-COUPLED MOS QUAD

```

VDD 1 0 5V
M1 14 3 5 0 N W=20U L=1U
M2 13 3 7 0 N W=20U L=1U
M3 13 4 8 0 N W=20U L=1U
M4 14 4 6 0 N W=20U L=1U
M5 9 9 5 1 P W=60U L=1U
M6 0 9 8 1 P W=60U L=1U
M7 0 12 7 1 P W=60U L=1U
M8 12 12 6 1 P W=60U L=1U
M9 13 13 1 1 P W=60U L=1U
M10 14 13 1 1 P W=60U L=1U
VOOUT 14 0 3.5V
IBIAS1 9 0 50UA
IBIAS2 12 0 50UA
.MODEL N NMOS KP=60U VTO=0.7
.MODEL P PMOS KP=20U VTO=-0.7
VS 3 21 SIN 0 0.1V 10K
EVS 4 22 3 21 -1
VBIAS1 21 0 3V
VBIAS2 22 0 3V
.PLOT TRAN I(VOOUT)
.TRAN 0.0025MS 0.2MS
.POUR 10K I(VOOUT)
.DC VS 0V 0.3V 0.02V
.PLOT DC I(VOOUT)
.OPTIONS NOPAGE NOMOD
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.END

```

***** DC TRANSFER CURVES THOM= 27.000 TEMP= 27.000

VOLT (A)	I(VOOUT)	0.	5.000E-05	1.000E-04	1.500E-04	2.000E-04
0.	2.99E-12	A				
2.000E-02	4.80E-07	A	+	+	+	+
4.000E-02	1.92E-06	A	+	+	+	+
6.000E-02	4.32E-06	A	+	+	+	+
8.000E-02	7.68E-06	A	+	+	+	+
1.000E-01	1.20E-05	A	+	+	+	+
1.200E-01	1.73E-05	A	+	+	+	+
1.400E-01	2.35E-05	A	+	+	+	+
1.600E-01	3.07E-05	A	+	+	+	+
1.800E-01	3.89E-05	A	+	+	+	+
2.000E-01	4.80E-05	A	+	+	+	+
2.200E-01	5.81E-05	A	+	+	+	+
2.400E-01	6.91E-05	A	+	+	+	+
2.600E-01	8.11E-05	A	+	+	+	+
2.800E-01	9.41E-05	A	+	+	+	+
3.000E-01	1.08E-04	A	+	+	+	+

VI=2*VS (V)	DESIRED 300U*VI*2 (UA)	ACTUAL IO (UA)
0.08	1.92	1.92
0.2	12	12
0.4	48	48

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

	= 5.000E+00 0:3	= 3.000E+00 0:4	= 3.000E+00
+0:1			
+0:5	= 2.011E+00 0:6	= 2.011E+00 0:7	= 2.011E+00
+0:8	= 2.011E+00 0:9	= 1.022E+00 0:12	= 1.022E+00
+0:13	= 3.891E+00 0:14	= 3.500E+00 0:21	= 3.000E+00
+0:22	= 3.000E+00		

**** MOSFETS

ELEMENT	0:M1	0:M2	0:M3	0:M4	0:M5	0:M6
MODEL	0:N	0:N	0:N	0:N	0:P	0:P
ID	5.000E-05	5.000E-05	5.000E-05	5.000E-05	-5.000E-05	-5.000E-05
IBS	-2.011E-14	-2.011E-14	-2.011E-14	-2.011E-14	2.989E-14	2.989E-14
IBD	-3.500E-14	-3.892E-14	-3.892E-14	-3.500E-14	3.977E-14	5.000E-14
VGS	9.887E-01	9.887E-01	9.887E-01	9.887E-01	-9.887E-01	-9.887E-01
VDS	1.488E+00	1.880E+00	1.880E+00	1.488E+00	-9.887E-01	-2.011E+00
VBS	-2.011E+00	-2.011E+00	-2.011E+00	-2.011E+00	2.988E+00	2.988E+00
VTH	7.000E-01	7.000E-01	7.000E-01	7.000E-01	-7.000E-01	-7.000E-01
VDSAT	2.887E-01	2.887E-01	2.887E-01	2.887E-01	-2.887E-01	-2.887E-01
BETA	1.200E-03	1.200E-03	1.200E-03	1.200E-03	1.200E-03	1.200E-03
GAM EFF	0.	0.	0.	0.	0.	0.
GM	3.464E-04	3.464E-04	3.464E-04	3.464E-04	3.464E-04	3.464E-04
ELEMENT	0:M7	0:M8	0:M9	0:M10		
MODEL	0:P	0:P	0:P	0:P		
ID	-5.000E-05	-5.000E-05	-1.000E-04	-1.000E-04		
IBS	2.989E-14	2.989E-14	0.	0.		
IBD	5.000E-14	3.977E-14	1.108E-14	1.500E-14		
VGS	-9.887E-01	-9.887E-01	-1.108E+00	-1.108E+00		
VDS	-2.011E+00	-9.887E-01	-1.108E+00	-1.500E+00		
VBS	2.988E+00	2.988E+00	0.	0.		
VTH	-7.000E-01	-7.000E-01	-7.000E-01	-7.000E-01		
VDSAT	-2.887E-01	-2.887E-01	-4.082E-01	-4.082E-01		
BETA	1.200E-03	1.200E-03	1.200E-03	1.200E-03		
GAM EFF	0.	0.	0.	0.		
GM	3.464E-04	3.464E-04	4.899E-04	4.899E-04		

***** TRANSIENT ANALYSIS

THOM= 27.000 TEMP= 27.000

TIME (A)	I(VOOUT)	0.	5.000E-06	1.000E-05	1.500E-05	2.000E-05
0.	2.99E-12	A				
2.500E-06	2.94E-07	A	+	+	+	+
5.000E-06	1.15E-06	A	+	+	+	+
7.500E-06	2.58E-06	A	+	+	+	+
1.000E-05	4.18E-06	A	+	+	+	+
1.250E-05	6.01E-06	A	+	+	+	+
1.500E-05	7.85E-06	A	+	+	+	+
1.750E-05	9.47E-06	A	+	+	+	+
2.000E-05	1.07E-05	A	+	+	+	+
2.250E-05	1.15E-05	A	+	+	+	+
2.500E-05	1.20E-05	A	+	+	+	+
2.750E-05	1.16E-05	A	+	+	+	+
3.000E-05	1.07E-05	A	+	+	+	+
3.250E-05	9.43E-06	A	+	+	+	+
3.500E-05	7.85E-06	A	+	+	+	+
3.750E-05	6.00E-06	A	+	+	+	+
4.000E-05	4.20E-06	A	+	+	+	+
4.250E-05	2.53E-06	A	+	+	+	+
4.500E-05	1.25E-06	A	+	+	+	+
4.750E-05	4.64E-07	A	+	+	+	+
5.000E-05	2.99E-12	A				
5.250E-05	3.28E-07	A	+	+	+	+
5.500E-05	1.30E-06	A	+	+	+	+
5.750E-05	2.51E-06	A	+	+	+	+
6.000E-05	4.20E-06	A	+	+	+	+
6.250E-05	5.99E-06	A	+	+	+	+
6.500E-05	7.85E-06	A	+	+	+	+
6.750E-05	9.42E-06	A	+	+	+	+
7.000E-05	1.09E-05	A	+	+	+	+
7.250E-05	1.15E-05	A	+	+	+	+
7.500E-05	1.20E-05	A	+	+	+	+
7.750E-05	1.16E-05	A	+	+	+	+
8.000E-05	1.07E-05	A	+	+	+	+
8.250E-05	9.43E-06	A	+	+	+	+
8.500E-05	7.85E-06	A	+	+	+	+
8.750E-05	6.00E-06	A	+	+	+	+
9.000E-05	4.20E-06	A	+	+	+	+
9.250E-05	2.53E-06	A	+	+	+	+
9.500E-05	1.25E-06	A	+	+	+	+
9.750E-05	4.64E-07	A	+	+	+	+
1.000E-04	2.99E-12	A				
1.025E-04	3.28E-07	A	+	+	+	+
1.050E-04	1.30E-06	A	+	+	+	+
1.075E-04	2.51E-06	A	+	+	+	+
1.100E-04	4.20E-06	A	+	+	+	+
1.125E-04	5.99E-06	A	+	+	+	+
1.150E-04	7.85E-06	A	+	+	+	+
1.175E-04	9.42E-06	A	+	+	+	+
1.200E-04	1.09E-05	A	+	+	+	+
1.225E-04	1.15E-05	A	+	+	+	+
1.250E-04	1.20E-05	A	+	+	+	+
1.275E-04	1.16E-05	A	+	+	+	+
1.300E-04	1.07E-05	A	+	+	+	+
1.325E-04	9.43E-06	A	+	+	+	+
1.350E-04	7.85E-06	A	+	+	+	+
1.375E-04	6.00E-06	A	+	+	+	+
1.400E-04	4.20E-06	A	+	+	+	+
1.425E-04	2.53E-06	A	+	+	+	+
1.450E-04	1.25E-06	A	+	+	+	+
1.475E-04	4.64E-07	A	+	+	+	+
1.500E-04	2.99E-12	A				
1.525E-04	3.28E-07	A	+	+	+	+
1.550E-04	1.30E-06	A	+	+	+	+
1.575E-04	2.51E-06	A	+	+	+	+
1.600E-04	4.20E-06	A	+	+	+	+
1.625E-04	5.99E-06	A	+	+	+	+
1.650E-04	7.85E-06	A	+	+	+	+
1.675E-04	9.42E-06	A	+	+	+	+
1.700E-04	1.09E-05	A	+	+	+	+
1.725E-04	1.15E-05	A	+	+	+	+
1.750E-04	1.20E-05	A	+	+	+	+
1.775E-04	1.16E-05	A	+	+	+	+
1.800E-04	1.07E-05	A	+	+	+	+
1.825E-04	9.43E-06	A	+	+	+	+
1.850E-04	7.85E-06	A	+	+	+	+
1.875E-04	6.00E-06	A	+	+	+	+
1.900E-04	4.20E-06	A	+	+	+	+
1.925E-04	2.53E-06	A	+	+	+	+
1.950E-04	1.25E-06	A	+	+	+	+
1.975E-04	4.64E-07	A	+	+	+	+
2.000E-04	2.99E-12	A				

10-19

FOURIER COMPONENTS OF TRANSIENT RESPONSE I(VOUT)

DC COMPONENT = 6.001D-06

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+03	2.547E-09	1.000E+00	-9.009E+01	0.
2	2.000E+04	5.900E-06	2.315E+03	-9.002E+01	6.485E-02
3	3.000E+04	2.579E-09	1.012E+00	-9.036E+01	-2.750E-01
4	4.000E+04	4.602E-09	1.806E+00	-1.443E+02	-5.427E+01
5	5.000E+04	4.049E-10	1.590E-01	-9.669E+01	-6.604E+00
6	6.000E+04	2.205E-08	8.654E+00	-1.104E+02	-2.033E+01
7	7.000E+04	2.342E-10	9.193E-02	-1.111E+02	-2.101E+01
8	8.000E+04	6.213E-09	2.439E+00	1.308E+02	2.209E+02
9	9.000E+04	2.968E-10	1.165E-01	-1.284E+02	-3.836E+01

TOTAL HARMONIC DISTORTION = 2.315E+05 PERCENT

THE SECOND HARMONIC COMPONENT IN IO IS MUCH LARGER THAN
THE FIRST HARMONIC COMPONENT. BECAUSE THE TRANSFER
FUNCTION IS $IO=K*VI^2$, WE EXPECT, IDEALLY, TO SEE ONLY
A SECOND HARMONIC COMPONENT AND NO FIRST HARMONIC
COMPONENT.

CHAPTER 11

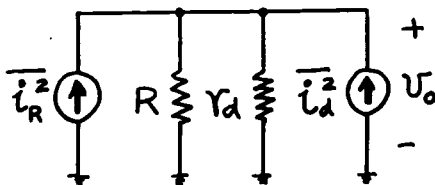
11.1

Diode current

$$I_D = \frac{10 - 0.6}{20k} = 470 \mu A$$

where k is kilo = 10^3

Equivalent circuit



$$r_d = \frac{kT}{qI_D} = \frac{26}{470} k\Omega = 55.3 \Omega$$

where k is the Boltzmann's const.

$$R = 20 k\Omega$$

$$r_d \parallel R = 55.3 \Omega$$

$$\therefore \overline{V_o^2} = (\overline{i_R^2} + \overline{i_d^2}) r_d^2$$

$$= 55.3^2 \left(4kT \frac{1}{R} + 2qI_D \right) \Delta f$$

$$= 3060 \left(\frac{1.66 \times 10^{-20}}{2 \times 10^4} + 3.2 \times 10^{-19} \times 470 \times 10^{-6} \right)$$

$$\begin{aligned} & \times \Delta f \\ & = 3060 \times 1.51 \times 10^{-22} \Delta f \end{aligned}$$

$$\therefore \frac{\overline{V_o^2}}{\Delta f} = 4.63 \times 10^{-19} \text{ V}^2/\text{Hz}$$

$$\text{If } \Delta f = 10^5 \text{ Hz}$$

$$\overline{V_{oT}^2} = 4.63 \times 10^{-19} \times 10^5$$

$$= 4.63 \times 10^{-14} \text{ V}^2$$

$$\therefore V_{oT} = 0.215 \mu\text{V rms}$$

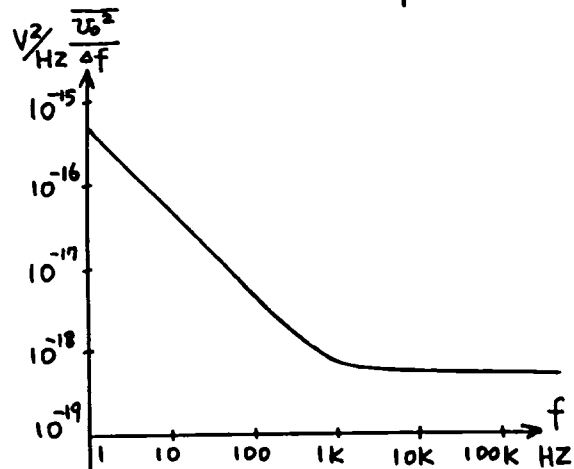
11.2

$$\overline{i_d^2} = 2qI_D \Delta f + 3 \times 10^{-16} \frac{I_D}{f} \Delta f$$

$$\begin{aligned} \therefore \frac{\overline{i_d^2}}{\Delta f} &= 3.2 \times 10^{-19} \times 470 \times 10^{-6} + 3 \times 10^{-16} \times \frac{470 \times 10^{-6}}{f} \\ &= 1.5 \times 10^{-22} + \frac{1.41 \times 10^{-19}}{f} \end{aligned}$$

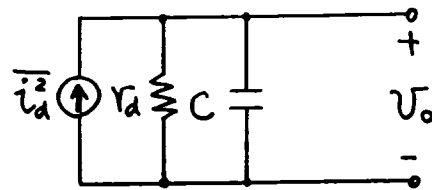
$$\therefore \overline{V_o^2} = 55.3^2 \times (\overline{i_d^2} + \overline{i_R^2})$$

$$\begin{aligned} \therefore \frac{\overline{V_o^2}}{\Delta f} &= 3060 \left(1.5 \times 10^{-22} + \frac{1.41 \times 10^{-19}}{f} \right) \\ &= 4.62 \times 10^{-19} + \frac{4.32 \times 10^{-16}}{f} \end{aligned}$$



11.3

Neglect R and noise in R.



$$V_o = i_d \frac{r_d}{1 + j\omega C r_d}$$

$$\overline{V_o^2} = \overline{i_d^2} \frac{r_d^2}{1 + (\omega r_d C)^2}$$

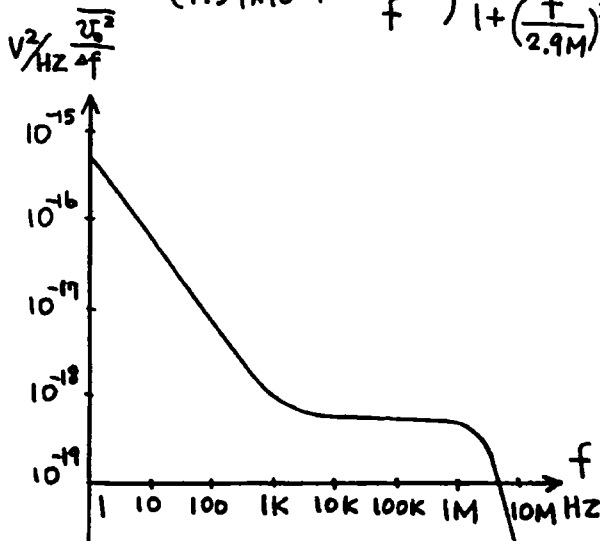
$$r_d = 55.3 \Omega, C = 1000 \text{ pF}$$

$$\therefore \frac{1}{r_d C} = 18.1 \times 10^6 \text{ rad/sec}$$

$$\therefore \frac{1}{2\pi r_d C} = 2.9 \text{ MHz}$$

$$\therefore \frac{\overline{V_o^2}}{\Delta f} = \left(1.5 \times 10^{-22} + \frac{1.41 \times 10^{-19}}{f} \right) \frac{3060}{1 + \left(\frac{f}{2.9 \text{ M}} \right)^2}$$

$$= \left(4.59 \times 10^{-19} + \frac{4.32 \times 10^{-16}}{f} \right) \frac{1}{1 + \left(\frac{f}{2.9 \text{ M}} \right)^2}$$



```
NOISE ANALYSIS
VCC 1 0 10V AC 1
RL 1 2 20K
DIODE 2 0 D
CAP 2 0 1MF
.NOISE V(2) VCC 10
.AC DEC 10 1 10MEG
.MODEL D D KP=3E-16 AP=1
.OPTIONS NOMOD SPICE
.WIDTH OUT=80
.END
```

```
***** OPERATING POINT INFORMATION      TNO= 27.000 TEMP= 27.000
+0:1      = 1.000E+01 0:2      = 6.355E-01
**** DIODES
ELEMENT 0:DIODE
MODEL 0:D
ID 4.682E-04
VD 6.355E-01
REQ 5.523E+01
CAP 0.
```

NOISE ANALYSIS

```
FREQUENCY = 1.000E+00 HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/Hz)
ELEMENT 0:RL
TOTAL 2.515E-21
**** DIODE SQUARED NOISE VOLTAGES (SQ V/Hz)
ELEMENT 0:DIODE
ID 4.553E-19
FW 4.263E-16
TOTAL 4.267E-16
**** TOTAL OUTPUT NOISE VOLTAGE = 4.267E-16 SQ V/Hz
```

```
FREQUENCY = 9.999E+00 HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/Hz)
ELEMENT 0:RL
TOTAL 2.515E-21
**** DIODE SQUARED NOISE VOLTAGES (SQ V/Hz)
ELEMENT 0:DIODE
ID 4.553E-19
FW 4.263E-17
TOTAL 4.308E-17
**** TOTAL OUTPUT NOISE VOLTAGE = 4.308E-17 SQ V/Hz
```

```
FREQUENCY = 1.000E+02 HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/Hz)
ELEMENT 0:RL
TOTAL 2.515E-21
**** DIODE SQUARED NOISE VOLTAGES (SQ V/Hz)
ELEMENT 0:DIODE
ID 4.553E-19
FW 4.263E-18
TOTAL 4.718E-18
**** TOTAL OUTPUT NOISE VOLTAGE = 4.720E-18 SQ V/Hz
```

```
FREQUENCY = 1.000E+03 HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/Hz)
ELEMENT 0:RL
TOTAL 2.515E-21
**** DIODE SQUARED NOISE VOLTAGES (SQ V/Hz)
ELEMENT 0:DIODE
ID 4.553E-19
FW 4.263E-19
TOTAL 8.815E-19
**** TOTAL OUTPUT NOISE VOLTAGE = 8.841E-19 SQ V/Hz
```

```
FREQUENCY = 9.999E+03 HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/Hz)
ELEMENT 0:RL
TOTAL 2.515E-21
**** DIODE SQUARED NOISE VOLTAGES (SQ V/Hz)
ELEMENT 0:DIODE
ID 4.553E-19
FW 4.262E-20
TOTAL 4.979E-19
**** TOTAL OUTPUT NOISE VOLTAGE = 5.004E-19 SQ V/Hz
```

```
FREQUENCY = 9.999E+04 HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/Hz)
ELEMENT 0:RL
TOTAL 2.512E-21
**** DIODE SQUARED NOISE VOLTAGES (SQ V/Hz)
ELEMENT 0:DIODE
ID 4.547E-19
FW 4.257E-21
TOTAL 4.590E-19
**** TOTAL OUTPUT NOISE VOLTAGE = 4.615E-19 SQ V/Hz
```

```
FREQUENCY = 1.000E+06 HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/Hz)
ELEMENT 0:RL
TOTAL 2.246E-21
**** DIODE SQUARED NOISE VOLTAGES (SQ V/Hz)
ELEMENT 0:DIODE
ID 4.066E-19
FW 3.807E-22
TOTAL 4.070E-19
**** TOTAL OUTPUT NOISE VOLTAGE = 4.092E-19 SQ V/Hz
```

```
FREQUENCY = 9.999E+06 HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/Hz)
ELEMENT 0:RL
TOTAL 1.938E-22
**** DIODE SQUARED NOISE VOLTAGES (SQ V/Hz)
ELEMENT 0:DIODE
ID 3.508E-20
FW 3.284E-24
TOTAL 3.508E-20
**** TOTAL OUTPUT NOISE VOLTAGE = 3.527E-20 SQ V/Hz
```

11.4

Using (11.38)

$$\begin{aligned} \frac{\overline{V_o^2}}{\Delta f} &= g_m^2 R_L^2 \frac{V_R^2}{(r_r + R_s)^2} \left[4kTR_s + R_s^2 2g I_0 \right] \\ &\quad + R_L^2 \left(4kT \frac{1}{R_L} + 2g I_C \right) \\ &= \frac{10^8}{26^2} \frac{50 \times 26^2}{2300^2} \left[1.66 \times 10^{-20} \times 10^3 + 10^6 \times 3.2 \times 10^{-19} \right. \\ &\quad \left. \times 20 \times 10^{-6} \right] + 10^8 \times 1.66 \times 10^{-20} \times 10^4 \\ &\quad + 10^8 \times 3.2 \times 10^{-19} \times 10^{-3} \end{aligned}$$

11-3

$$= 4.73 \times 10^{-12} [1.66 \times 10^{-17} + 6.4 \times 10^{-18}]$$

$$+ 1.66 \times 10^{-16} + 3.2 \times 10^{-14}$$

$$= 1.12 \times 10^{-12} \text{ V}^2/\text{HZ}$$

$$\text{If } \Delta f = 2 \text{ MHz}$$

$$\overline{V_{OT}^2} = 1.12 \times 10^{-12} \times 2 \times 10^6 \text{ V}^2$$

$$= 2.24 \times 10^{-6} \text{ V}^2$$

$$\therefore V_{OT} = 1.5 \text{ mV rms}$$

Circuit gain

$$G = \left| \frac{V_O}{i_s} \right| = \frac{R_s r_\pi}{R_s + r_\pi} g_m R_L$$

$$= \frac{1 \times 1.3}{2.3} \times 1000 \times \frac{10,000}{26}$$

$$= 2.17 \times 10^5 \Omega$$

$$\text{MDS} = \frac{V_{OT}}{G} = 6.9 \text{ nA}$$

**** TRANSISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)

ELEMENT 0:Q1

RB 0.

RC 0.

RE 0.

IB 3.045E-13

IC 3.204E-14

FW 0.

TOTAL 3.366E-13

**** TOTAL OUTPUT NOISE VOLTAGE

= 1.125E-12 SQ V/HZ

= 1.060E-06 V/RT HZ

TRANSFER FUNCTION VALUE:

V(2)/IS

= 2.180E+05

EQUIVALENT INPUT NOISE AT IS

= 4.864E-12 /RT HZ

COMMON EMITTER CONFIGURATION

```
VCC 1 0 15V
RL 1 2 10K
Q1 2 3 0 N
RS 3 0 1K
IS 0 3 794.20A AC 1
.NOISE V(2) IS 10
.AC DEC 10 0.2MEG 20MEG
.PLOT AC V(2)
.MODEL N MPN BF=50
.WIDTH OUT=80
.OPTIONS NOMOD SPICE
.WIDTH OUT=80
.END
```

```
***** OPERATING POINT INFORMATION      TNOH= 27.000 TEMP= 27.000
+0:1      = 1.500E+01 0:2      = 5.001E+00 0:3      = 7.742E-01
```

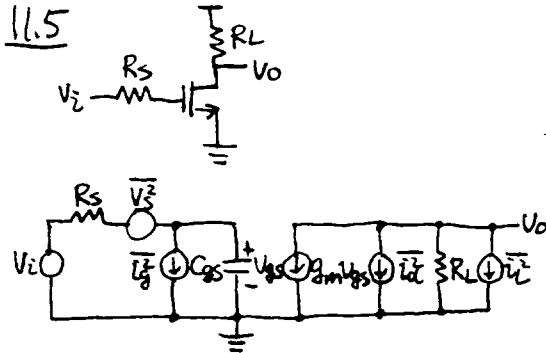
**** BIPOLAR JUNCTION TRANSISTORS

```
ELEMENT 0:Q1
MODEL 0:N
IB 2.000E-05
IC 9.998E-04
VBE 7.742E-01
VCE 5.001E+00
VBC -4.227E+00
VS -5.001E+00
POWER 5.016E-03
BETAD 5.000E+01
GM 3.866E-02
RPI 1.293E+03
RX 0.
RO 4.227E+16
CFI 0.
CMF 0.
CBI 0.
CCS 0.
BETAAC 5.000E+01
FT 6.152E+12
```

```
***** NOISE ANALYSIS      TNOH= 27.000 TEMP= 27.000
FREQUENCY = 2.000E+06 HZ
```

**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)

```
ELEMENT 0:RL 0:RS
TOTAL 1.658E-16 7.878E-13
```



$$g_m = \sqrt{2 \times (94 \times 100 \times 100)} = 1.97 \text{ mA/V}$$

$$C_{ox} = 4.3 \text{ fF}/\mu\text{m}^2$$

$$A_v(\omega) = \frac{V_o}{V_i}(\omega) = -\frac{g_m R_L}{1 + 5C_{gs}R_s}$$

$$C_{gs} = \frac{2}{3} 100 \times 1 \times 4.3 = 287 \text{ fF}$$

$$f_{-3dB} = \frac{1}{2\pi C_{gs}R_s} = 5.55 \text{ MHz}$$

$$\overline{V_s^2} = 4kTR_s \Delta f$$

$$\overline{i_g^2} = 2qI_g \Delta f \approx 0$$

$$\overline{i_d^2} = \frac{4kT}{R_L} \Delta f$$

$$\overline{i_L^2} = 4kT \frac{2}{3} g_m \Delta f + \frac{g_m^2 K_f \Delta f}{WL C_{ox} f}$$

$$\overline{V_s^2} \text{ produces } \overline{V_{o1}^2} = A_v^2(\omega) \overline{V_s^2}$$

$$\overline{i_d^2} \text{ produces } \overline{V_{o2}^2} = \overline{i_d^2} R_L^2$$

$$\overline{i_L^2} \text{ produces } \overline{V_{o3}^2} = \overline{i_L^2} R_L^2$$

$$\text{At } 10 \text{ Hz, } |A_v| = 19.7$$

$$\overline{V_{o1}^2} = (19.7)^2 (1.66 \times 10^{-20}) (10^5) \Delta f$$

$$= 6.44 \times 10^{-13} \Delta f (\text{V}^2)$$

$$\overline{V_{o2}^2} = (1.66 \times 10^{-20}) \frac{2}{3} (1.97 \times 10^3 \times (10^4)^2) \Delta f$$

$$+ \frac{(1.97 \times 10^3)^2 (3 \times 10^{-24}) \Delta f (10^4)^2}{100(1)(4.3 \times 10^{-15})10}$$

$$= [2.18 \times 10^{-15} + 2.71 \times 10^{-10}] \Delta f (\text{V}^2)$$

$$\overline{V_{o3}^2} = 1.66 \times 10^{-20} (10^4) \Delta f = 1.66 \times 10^{-16} \Delta f (\text{V}^2)$$

$$\overline{V_{oT}^2} = \overline{V_{o1}^2} + \overline{V_{o2}^2} + \overline{V_{o3}^2} = 2.72 \times 10^{-10} \Delta f (\text{V}^2)$$

$$\sqrt{\overline{V_{oT}^2}} = 16.5 \text{ nV} \sqrt{\Delta f}$$

Total input-referred noise

$$\sqrt{\overline{V_{iT}^2}} = \sqrt{\overline{V_{oT}^2}} / |A_v| = 837 \text{ nV} \sqrt{\Delta f}$$

$$\text{At } 100 \text{ kHz, } |A_v| \approx 19.7$$

$$\overline{V_{o1}^2} = 6.44 \times 10^{-13} \Delta f (\text{V}^2) \text{ (same)}$$

$$\overline{V_{o2}^2} = (2.18 \times 10^{-15} + 2.71 \times 10^{-10}) \Delta f (\text{V}^2)$$

$$\overline{V_{o3}^2} = 1.66 \times 10^{-16} \Delta f (\text{V}^2) \text{ (same)}$$

$$\overline{V_{oT}^2} = 6.73 \times 10^{-13} \Delta f (\text{V}^2)$$

$$\sqrt{\overline{V_{oT}^2}} = 821 \text{ nV} \sqrt{\Delta f}$$

$$\sqrt{\overline{V_{iT}^2}} = 41.7 \text{ nV} \sqrt{\Delta f}$$

$$\text{At } 1 \text{ GHz, } |A_v| = 19.7 / \sqrt{1 + (1000/5.55)^2} = 0.109$$

$$\overline{V_{o1}^2} = (0.109)^2 (1.66 \times 10^{-20}) (10^9) \Delta f$$

$$= 1.98 \times 10^{-17} \Delta f (\text{V}^2)$$

$$\overline{V_{o2}^2} = (2.18 \times 10^{-15} + 2.71 \times 10^{-10}) \Delta f (\text{V}^2)$$

$$\overline{V_{o3}^2} = 1.66 \times 10^{-16} \Delta f (\text{V}^2) \text{ (same)}$$

$$\overline{V_{oT}^2} = 2.37 \times 10^{-15} \Delta f (\text{V}^2)$$

$$\sqrt{\overline{V_{oT}^2}} = 48.7 \text{ nV} \sqrt{\Delta f}$$

$$\sqrt{\overline{V_{iT}^2}} = 48.7 \text{ nV} \sqrt{\Delta f} / 0.109 = 446 \text{ nV} \sqrt{\Delta f}$$

At 10 Hz, 1/f noise dominates

At 100 kHz, thermal noise from R_s dominates

At 1 GHz, thermal noise from the transistor dominates.

11-5

```

COMMON-SOURCE AMP NOISE SIMULATION
VDD 1 0 5
VI 2 0 DC 0.70154 AC 1
M1 3 4 0 0 CMOSN L=1U W=100U
RL 1 3 10K
RS 2 4 100K
.MODEL CMOSN NMOS LEVEL=1 VTO=0.6 KP=194U KP=3E-24 TOX=80E-10 CAPOP=0
.OPTIONS NOMOD
.WIDTH OUT=80
.OP
.AC DEC 10 10 1GIG
.NOISE V(3) VI 40
.PRINT AC VM(3) ONOISE INOISE
.END

***** OPERATING POINT INFORMATION THOM= 25.000 TEMP= 25.000

+0:1 = 5.0000 0:2 = 701.5400M 0:3 = 3.9999
+0:4 = 701.5400M

**** MOSFETS

ELEMENT 0:M1
MODEL 0:CMOSN
ID 100.0106U
IBS 0.
IBD -39.9989F
VGS 701.5400M
VDS 3.9999
VBS 0.
VTH 600.0000M
VDSAT 101.5400M
BETA 19.4000M
GAM EFF 42.2100M
GM 1.9699M
GDS 0.
GMB 54.5972U
CUTOT 0.
CGTOT 287.7634F
CSTOT 287.7634F
CBTOT 0.
CGS 287.7634F
CGD 0.

***** NOISE ANALYSIS THOM= 25.000 TEMP= 25.000
FREQUENCY = 10.0000 HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT 0:RL 0:RS
TOTAL 1.647E-16 638.9216F
**** MOSFET SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT 0:M1
ID 2.1623F
RX 10.0000K
FY 269.6959F
TOTAL 269.6981F
**** TOTAL OUTPUT NOISE VOLTAGE = 270.3372F SQ V/HZ
= 16.4419U V/RT HZ

TRANSFER FUNCTION VALUE:
V(3)/VI = 19.6988
EQUIVALENT INPUT NOISE AT VI = 834.6685M /RT HZ

***** NOISE ANALYSIS THOM= 25.000 TEMP= 25.000
FREQUENCY = 100.0000K HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT 0:RL 0:RS
TOTAL 1.647E-16 638.7128F
**** MOSFET SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT 0:M1
ID 2.1623F
RX 10.0000K
FY 26.9696F
TOTAL 29.1319F
**** TOTAL OUTPUT NOISE VOLTAGE = 668.0094F SQ V/HZ
= 817.3184M V/RT HZ

TRANSFER FUNCTION VALUE:
V(3)/VI = 19.6955
EQUIVALENT INPUT NOISE AT VI = 41.4976M /RT HZ

***** NOISE ANALYSIS THOM= 25.000 TEMP= 25.000
FREQUENCY = 1.0000G HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT 0:RL 0:RS
TOTAL 1.647E-16 1.954E-17
**** MOSFET SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT 0:M1
ID 2.1623F
RX 10.0000K
FY 2.697E-18
TOTAL 2.1650F
**** TOTAL OUTPUT NOISE VOLTAGE = 2.3492F SQ V/HZ
= 48.4686M V/RT HZ

TRANSFER FUNCTION VALUE:
V(3)/VI = 108.9474M
EQUIVALENT INPUT NOISE AT VI = 444.8804M /RT HZ

***** AC ANALYSIS THOM= 25.000 TEMP= 25.000
FREQ VOLTAGE M ONOISE INOISE
10.00000 19.6988 16.4419U 834.6685M
12.58925 19.6988 14.6584U 744.1275M
15.84893 19.6988 13.0693U 663.4605M
19.95262 19.6988 11.6537U 591.5971M
25.11886 19.6988 10.3927U 527.5837M
31.62278 19.6988 9.2697U 470.5707M
39.81072 19.6988 8.2696U 419.8016M
50.11872 19.6988 7.3792U 374.6025M
63.09574 19.6988 6.5867U 334.3734M
79.43282 19.6988 5.8817U 298.5803M
100.00000 19.6988 5.2546U 266.7479M
125.89254 19.6988 4.6972U 238.4530M
158.48932 19.6988 4.2021U 213.3196M
199.52623 19.6988 3.7627U 191.0131M
251.18864 19.6988 3.3731U 171.2359M
316.22776 19.6988 3.0282U 153.7236M
398.10717 19.6988 2.7232U 138.2411M
501.18723 19.6988 2.4541U 124.5792M
630.95734 19.6988 2.2171U 112.5515M
794.32826 19.6988 2.0091U 101.9916M
1.000000E 19.6988 1.8271U 92.7508M
1.258933E 19.6988 1.6684U 84.6951M
1.584893E 19.6988 1.5307U 77.7033M
1.995266E 19.6988 1.4117U 71.6650M
2.511893E 19.6988 1.3096U 66.4789M
3.162288E 19.6988 1.2223U 62.0514M
3.981070E 19.6988 1.1483U 58.2953M
5.011878E 19.6988 1.0860U 55.1296M
6.309570E 19.6987 1.0338U 52.4791M
7.943280E 19.6987 990.3405M 50.2743M
10.000000E 19.6987 954.4330M 48.4515M
12.589255E 19.6987 924.9174M 46.9532M
15.848933E 19.6987 900.7830M 45.7281M
19.952623E 19.6986 881.1404M 44.7310M
25.118878E 19.6986 865.2166M 43.9229M
31.622780E 19.6984 852.3573M 43.2703M
39.810728E 19.6982 841.9976M 42.7448M
50.118728E 19.6980 833.6711M 42.3227M
63.095733E 19.6975 826.9881M 41.9845M
79.432828E 19.6967 821.6261M 42.7138M
100.000000E 19.6955 817.3184M 41.4976M
125.892544E 19.6937 813.8432M 41.3251M
158.489328E 19.6907 811.0123M 41.1876M
199.526233E 19.6860 808.6624M 41.0781M
251.188644E 19.6785 806.6413M 40.9910M
316.227766E 19.6666 804.7951M 40.9218M
398.107158E 19.6479 802.9506M 40.8669M
501.187233E 19.6184 800.8906M 40.8235M
630.957368E 19.5718 799.3198M 40.7893M
794.328244E 19.4987 794.8152M 40.7625M
1.0000000E 19.3845 789.7592M 40.7419M
1.2589333E 19.2075 782.2516M 40.7265M
1.5848933E 19.9366 771.0159M 40.7157M
1.9952666E 18.5298 754.3361M 40.7093M
2.5118933E 17.9356 730.1156M 40.7075M
3.1622888E 17.1009 696.1968M 40.7112M
3.9810708E 15.3877 651.0514M 40.7220M
5.0118708E 14.5970 594.7236M 40.7429M
6.3095708E 12.9849 529.4999M 40.7793M
7.9432808E 11.2561 459.6542M 40.8362M
10.0000000E 9.5339 390.2023M 40.9282M
12.5892558E 7.9232 325.4326M 41.0732M
15.8489333E 6.4904 268.0620M 41.3014M
19.9526233E 5.2620 219.2073M 41.6569M
25.1188668E 4.2359 178.8224M 42.2161M
31.6227808E 3.3938 146.2063M 43.0810M
39.8107208E 2.7106 120.3857M 44.4122M
50.1187208E 2.1607 100.3366M 46.4379M
63.0957338E 1.7201 85.0972M 49.4714M
79.4328208E 1.3681 73.7801M 53.9222M
100.0000000E 1.0878 65.5526M 60.2962M
125.8925448E 864.5791M 59.8261M 69.1968M
158.4893288E 687.0039M 55.8668M 81.3195M
199.5262338E 545.8291M 53.2074M 97.4800M
251.188658E 433.6289M 51.4519M 118.6543M
316.227768E 344.4744M 50.3078M 146.9421M
398.107178E 273.6412M 49.5684M 181.1438M
501.187228E 217.3687M 49.0932M 225.8520M
630.957348E 172.6660M 48.7886M 282.5604M
794.328238E 137.1554M 48.5925M 354.2953M
999.999988E 108.9474M 48.4686M 444.8824M

```

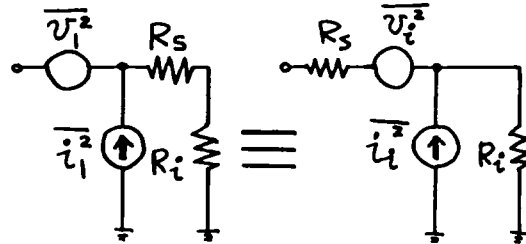
11-6

$$\therefore i_x = 6.8 \text{ nA rms}$$

---- the same as in 11.4

11.7

(a)(i)



Short inputs and equate noise

$$v_1 = v_i + i_i R_s$$

$$\therefore \overline{v_1^2} = \overline{v_i^2} + \overline{i_i^2} R_s^2$$

neglecting correlation

Open inputs and equate noise

$$i_1^2 = i_i^2$$

for the transistor plus R_s

(neglect R_L)

$$\overline{v_i^2} = 4kT(r_b + \frac{1}{2g_m} + R_s)\Delta f$$

$$= 1.66 \times 10^{-20} (100 + 26 + 10^5) \Delta f$$

$$\frac{\overline{v_i^2}}{\Delta f} = 1.66 \times 10^{-15} \frac{\text{V}^2}{\text{Hz}}$$

$$\overline{i_i^2} = 2q(I_B + \frac{I_C}{\beta^2})\Delta f$$

$$\frac{\overline{i_i^2}}{\Delta f} = 3.2 \times 10^{-19} (5 \times 10^{-6})$$

$$= 16 \times 10^{-25} \frac{\text{A}^2}{\text{Hz}} = \frac{\overline{i_1^2}}{\Delta f}$$

$$\frac{\overline{v_1^2}}{\Delta f} = 1.66 \times 10^{-15} + 16 \times 10^{-25} \times 10^{10}$$

$$= 17.7 \times 10^{-15} \frac{\text{V}^2}{\text{Hz}}$$

11.6

Neglect R_L

$$\overline{v_i^2} = 4kT(r_b + \frac{1}{2g_m})\Delta f$$

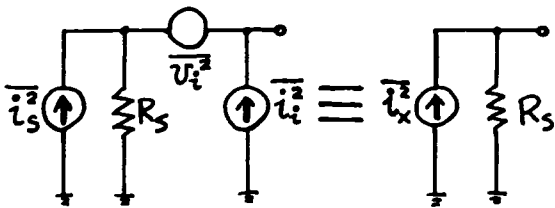
$$\therefore \frac{\overline{v_i^2}}{\Delta f} = 1.66 \times 10^{-20} \times 13 \frac{\text{V}^2}{\text{Hz}}$$

$$= 21.6 \times 10^{-20} \frac{\text{V}^2}{\text{Hz}}$$

$$\frac{\overline{i_i^2}}{\Delta f} = 2q(I_B + \frac{I_C}{\beta^2})$$

$$= 3.2 \times 10^{-19} \times 20 \times 10^{-6} \frac{\text{A}^2}{\text{Hz}}$$

$$= 6.4 \times 10^{-24} \frac{\text{A}^2}{\text{Hz}}$$



Equate voltage across R_s

$$i_s R_s + i_i R_s + v_i = i_x R_s$$

$$\therefore \overline{i_x^2} = \overline{i_s^2} + \overline{i_i^2} + \frac{\overline{v_i^2}}{R_s^2}$$

$$\therefore \frac{\overline{i_x^2}}{\Delta f} = 4kT \frac{1}{R_s} + 64 \times 10^{-25} + \frac{21.6 \times 10^{-20}}{10^6}$$

$$= 1.66 \times 10^{-23} + 0.64 \times 10^{-23} + 0.02 \times 10^{-23}$$

$$= 2.32 \times 10^{-23} \frac{\text{A}^2}{\text{Hz}}$$

If $\Delta f = 2 \text{ MHz}$

$$\overline{i_x^2} = 2.32 \times 10^{-23} \times 2 \times 10^6$$

$$= 4.64 \times 10^{-17} \text{ A}^2$$

11-7

(ii)

$$\overline{v_i^2} = 4kT(R_b + R_E + \frac{1}{2g_m})\Delta f + 4kT\frac{1}{R_L}\Delta f R_E^2$$

$$\therefore \frac{\overline{v_i^2}}{\Delta f} = 1.66 \times 10^{-20} (100 + 1000 + 26 + 100)$$

$$= 2.04 \times 10^{-17} \text{ V}^2$$

$$\frac{\overline{i_i^2}}{\Delta f} = 2g(I_B + \frac{I_C}{\beta^2}) = 16 \times 10^{-25} \text{ A}^2/\text{Hz}$$

(iii)

$$\frac{\overline{v_i^2}}{\Delta f} = 4kT(R_b + \frac{1}{2g_m}) + \frac{4kT\frac{1}{R_L}}{g_m^2}$$

$$= 1.66 \times 10^{-20} (100 + 1000 + 400)$$

$$= 2.49 \times 10^{-17} \text{ V}^2/\text{Hz}$$

$$\frac{\overline{i_i^2}}{\Delta f} \approx 2g(I_B) = 3.2 \times 10^{-19} \times \frac{13 \times 10^{-6}}{50}$$

$$= 8.32 \times 10^{-26} \text{ A}^2/\text{Hz}$$

(iv)

$$\frac{\overline{v_i^2}}{\Delta f} = 4kT\frac{2}{3}\frac{1}{g_m} + \frac{4kT\frac{1}{R_L}}{g_m^2}$$

$$= 4kT\frac{1}{g_m}(0.67 + \frac{1}{10})$$

$$= 1.66 \times 10^{-20} \times 1000 \times 0.77$$

$$= 1.28 \times 10^{-17} \text{ V}^2/\text{Hz}$$

$$\frac{\overline{i_i^2}}{\Delta f} \approx 0$$

$$(b)(i) \overline{v_{iT}} = 17.7 \times 10^{-15} \times 20,000 \text{ V}^2$$

$$v_{iT} = 18.8 \mu\text{V rms}$$

$$(ii) \overline{v_{iT}} = 2.04 \times 10^{-17} \times 20,000 \text{ V}^2$$

$$\therefore v_{iT} = 0.64 \mu\text{V rms}$$

$$(iii) \overline{v_{iT}} = 2.49 \times 10^{-17} \times 20,000 \text{ V}^2$$

$$\therefore v_{iT} = 0.71 \mu\text{V rms}$$

$$(iv) \overline{v_{iT}} = 1.28 \times 10^{-17} \times 20,000 \text{ V}^2$$

$$\therefore v_{iT} = 0.5 \mu\text{V rms}$$

Thus the FET is best and (i) is worst.

11.8

For the FET

$$\frac{\overline{i_d^2}}{\Delta f} = 4kT(\frac{2}{3}g_m) + K\frac{I_D^a}{f}$$

$$4kT\frac{2}{3}g_m = \frac{KI_D^a}{10^5}$$

$$\therefore \frac{\overline{i_d^2}}{\Delta f} = 4kT(\frac{2}{3}g_m)(1 + \frac{10^5}{f})$$

$$\frac{\overline{v_i^2}}{\Delta f} = 4kT\frac{2}{3}g_m(1 + \frac{10^5}{f})$$

$$\frac{\overline{i_i^2}}{\Delta f} = 2gI_G \approx 0$$

$$\overline{v_{iT}} = \int_{f_1}^{f_2} 4kT\frac{2}{3}g_m(1 + \frac{10^5}{f}) df$$

$$= 1.66 \times 10^{-20} \times \frac{2000}{3} \left[(f_2 - f_1) + 10^5 \ln \frac{f_2}{f_1} \right]$$

$$= 1.1 \times 10^{-17} [20,000 + 10^5 \ln \frac{20,000}{0.001}]$$

$$= 1.1 \times 10^{-17} [20,000 + 1.68 \times 10^6]$$

$$= 1.9 \times 10^{-11} \text{ V}^2$$

$$\therefore v_{iT} = 4.3 \mu\text{V rms}$$

11.9

bias

$$V_{BE} = V_T \ln \frac{I_C}{I_S}$$

$$= (26\text{m}) \ln \frac{10^{-3}}{10^{-16}}$$

$$= 0.778\text{V}$$

$$I_D = \frac{0.778 + 0.1}{300}$$

$$= 2.93\text{mA}$$

$$\text{mos } g_m = \sqrt{2 I_D \mu C_{ox} \frac{W}{L}}$$

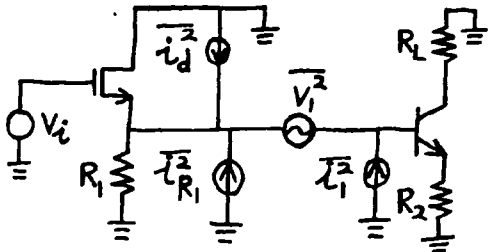
$$= \sqrt{2(2.93\text{m})(60\mu)(100)}$$

$$= 5.93\text{mA/V}$$

input noise current generator

= 0 (mosfets have
very small input noise
current at low freq)

input noise voltage generator



$$\overline{i_d^2} = 4kT \frac{2}{3} g_m \Delta f$$

$$\overline{i_{R_1}^2} = 4kT \frac{1}{300} \Delta f$$

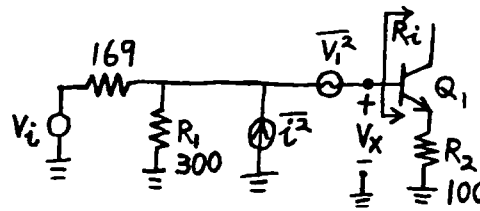
$$\overline{i_1^2} = 2q I_{B_1} \Delta f = 4kT \frac{2q I_{B_1}}{4kT} \Delta f$$

$$\overline{V_1^2} = 4kT (r_b + \frac{1}{2g_m} + R_2) \Delta f$$

neglect R_3 looking into source of m_1 ,

$$\text{we see } \frac{1}{g_m} = 169\Omega$$

11-8



$$\overline{i^2} = \overline{i_d^2} + \overline{i_{R_1}^2} + \overline{i_1^2}$$

$$= 4kT(3.95\text{m} + 3.33\text{m} + 0.19\text{m}) \Delta f$$

$$= 4kT 7.47\text{m} \Delta f$$

$$\overline{V_x^2} = \overline{V_1^2} \left[\frac{R_i}{R_i + (169 \parallel 300)} \right]^2 + \overline{i^2} (169 \parallel 300 \parallel R_i)^2$$

$$R_i \gg (169 \parallel 300)$$

$$\therefore \overline{V_x^2} = \overline{V_1^2} + \overline{i^2} (169 \parallel 300)^2$$

$$= 4kT(100 + 13 + 100) \Delta f$$

$$+ 4kT(7.47\text{m}) \Delta f (11.7\text{k})$$

equivalent input noise voltage = $\overline{V_i^2}$

$$\overline{V_i^2} \left(\frac{300}{469} \right)^2 = \overline{V_x^2}$$

$$0.41 \overline{V_i^2} = 4kT 300 \Delta f$$

$$\frac{\overline{V_i^2}}{\Delta f} = 1.66 \times 10^{-20} (300) \frac{1}{0.41}$$

$$= 1.22 \times 10^{-17} \frac{\text{V}^2}{\text{Hz}}$$

```

BICMOS DARLINGTON
VCC 1 0 5V
M1 1 2 3 0 NMOS W=100U L=1U
R1 3 0 300
Q1 5 3 4 NPN
R2 4 0 100
R3 1 5 2K
VI 2 0 2.5646V AC 1
.NOISE V(5) VI 10
.AC DEC 10 1K 1MEG
.MODEL NPN NPN BF=100 RB=100 IS=1E-16
.MODEL NMOS NMOS KP=60U VTO=0.7V
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.PROBE
.END

```

```

***** OPERATING POINT INFORMATION          TNOM= 27.000 TEMP= 27.000

```

```

+0:1      = 5.000E+00 0:2      = 2.564E+00 0:3      = 8.762E-01
+0:4      = 1.010E-01 0:5      = 2.999E+00

```

```

**** BIPOLAR JUNCTION TRANSISTORS

```

```

ELEMENT 0:Q1
MODEL 0:NPN
IB 1.000E-05
IC 1.000E-03
VBE 7.752E-01
VCE 2.898E+00
VBC -2.123E+00
VS -2.999E+00
POWER 2.907E-03
BETAD 1.000E+02
GM 3.867E-02
RPI 2.586E+03
RX 1.000E+02
RO 2.124E+16
CPI 0.
CMU 0.
CBX 0.
CCS 0.
BETAAC 9.999E+01
FT 6.153E+12

```

```

**** MOSFETS

```

```

ELEMENT 0:M1
MODEL 0:NMOS
ID 2.931E-03
IBS -8.762E-15
IRD -5.000E-14
VGS 1.688E+00
VDS 4.123E+00
VBS -8.762E-01
VTH 7.000E-01
VDSAT 9.884E-01
BETA 6.000E-03
GAM EFF 0.
GM 5.930E-03
GDS 0.
GMB 0.
CDTOT 0.
CGTOT 0.
CSTOT 0.
CBTOT 0.
CGS 0.
CGD 0.

```

```

***** NOISE ANALYSIS          TNOM= 27.000 TEMP= 27.000

```

```

FREQUENCY = 1.000E+03 HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)

```

```

ELEMENT 0:R1 0:R2 0:R3
TOTAL 1.549E-16 3.988E-16 3.315E-17
**** TRANSISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)

```

```

ELEMENT 0:Q1
RB 3.988E-16
RC 0.
RE 0.
IB 7.311E-17
IC 6.458E-17
FN 0.
TOTAL 5.365E-16

```

```

**** MOSFET SQUARED NOISE VOLTAGES (SQ V/HZ)

```

```

ELEMENT 0:M1
RD 0.
RS 0.
ID 1.837E-16
RX 1.674E+03
FW -4.019E-03
TOTAL -4.019E-03

```

```

**** TOTAL OUTPUT NOISE VOLTAGE          =-4.019E-03 SQ V/HZ
                                           =-2.395E+00 V/RT HZ

```

```

TRANSFER FUNCTION VALUE:
V(5)/VI = 9.929E+00
EQUIVALENT INPUT NOISE AT VI =-2.413E-01 /RT HZ

```

```

BICMOS DARLINGTON
VCC 1 0 5V
M1 1 2 3 0 NMOS W=100U L=1U
R1 3 0 300
Q1 5 3 4 NPN
R2 4 0 100
R3 1 5 2K
VI 2 0 2.5646V AC 1
.NOISE V(5) VI 10
.AC DEC 80 10MEG 10GIG
*****
* ADJUST CJE TO ACHIEVE THE SPECIFIED FT=10GHZ FOR Q1
*****
.MODEL NPN NPN BF=100 RB=100 IS=1E-16 CJE=330FF CJC=50FF
.MODEL NMOS NMOS KP=60U VTO=0.7V TOX=153E-10 CBS=50FF
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.PROBE
.END

```

```

***** OPERATING POINT INFORMATION          TNOM= 27.000 TEMP= 27.000

```

```

+0:1      = 5.000E+00 0:2      = 2.564E+00 0:3      = 8.762E-01
+0:4      = 1.010E-01 0:5      = 2.999E+00

```

```

**** BIPOLAR JUNCTION TRANSISTORS

```

```

ELEMENT 0:Q1
MODEL 0:NPN
IB 1.000E-05
IC 1.000E-03
VBE 7.752E-01
VCE 2.898E+00
VBC -2.123E+00
VS -2.999E+00
POWER 2.907E-03
BETAD 1.000E+02
GM 3.867E-02
RPI 2.586E+03
RX 1.000E+02
RO 2.124E+16
CPI 5.605E-13
CMU 3.209E-14
CBX 0.
CCS 0.
BETAAC 9.999E+01
FT 1.038E+10

```

```

**** MOSFETS

```

```

ELEMENT 0:M1
MODEL 0:NMOS
ID 2.931E-03
IBS -8.762E-15
IRD -5.000E-14
VGS 1.688E+00
VDS 4.123E+00
VBS -8.762E-01
VTH 7.000E-01
VDSAT 9.884E-01
BETA 6.000E-03
GAM EFF 0.
GM 5.930E-03
GDS 0.
GMB 0.
CDTOT 1.241E-15
CGTOT 1.549E-13
CSTOT 1.850E-13
CBTOT 3.772E-14
CGS 1.505E-13
CGD 1.241E-15

```

```

***** NOISE ANALYSIS          TNOM= 27.000 TEMP= 27.000

```

```

FREQUENCY = 9.999E+06 HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)

```

```

ELEMENT 0:R1 0:R2 0:R3
TOTAL 1.549E-16 3.987E-16 3.315E-17
**** TRANSISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)

```

```

ELEMENT 0:Q1
RB 3.987E-16
RC 0.
RE 0.
IB 7.310E-17
IC 6.458E-17
FN 0.
TOTAL 5.364E-16

```

```

**** MOSFET SQUARED NOISE VOLTAGES (SQ V/HZ)

```

```

ELEMENT 0:M1
RD 0.
RS 0.
ID 1.837E-16
RX 1.674E+03
FW 0.
TOTAL 1.837E-16

```

```

**** TOTAL OUTPUT NOISE VOLTAGE          = 1.307E-15 SQ V/HZ

```

```

= 3.615E-08 V/RT HZ
TRANSFER FUNCTION VALUE:
V(5)/VI = 9.928E+00
EQUIVALENT INPUT NOISE AT VI = 3.641E-09 /RT HZ
***** LOW FREQ EQUIVALENT INPUT NOISE VOLTAGE = 1.33E-17 SQ V/HZ

***** NOISE ANALYSIS          THOM= 27.000 TEMP= 27.000
FREQUENCY = 1.333E+07 HZ
**** TOTAL OUTPUT NOISE VOLTAGE = 1.307E-15 SQ V/HZ
= 3.615E-08 V/RT HZ

TRANSFER FUNCTION VALUE:
V(5)/VI = 9.928E+00
EQUIVALENT INPUT NOISE AT VI = 3.641E-09 /RT HZ

***** NOISE ANALYSIS          THOM= 27.000 TEMP= 27.000
FREQUENCY = 1.333E+09 HZ
**** TOTAL OUTPUT NOISE VOLTAGE = 3.658E-16 SQ V/HZ
= 1.913E-08 V/RT HZ

TRANSFER FUNCTION VALUE:
V(5)/VI = 5.082E+00
EQUIVALENT INPUT NOISE AT VI = 3.763E-09 /RT HZ

***** NOISE ANALYSIS          THOM= 27.000 TEMP= 27.000
FREQUENCY = 4.217E+09 HZ
**** TOTAL OUTPUT NOISE VOLTAGE = 8.313E-17 SQ V/HZ
= 9.118E-09 V/RT HZ

TRANSFER FUNCTION VALUE:
V(5)/VI = 2.044E+00
EQUIVALENT INPUT NOISE AT VI = 4.460E-09 /RT HZ

***** NOISE ANALYSIS          THOM= 27.000 TEMP= 27.000
FREQUENCY = 7.498E+09 HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT 0:R1 0:R2 0:R3
TOTAL 1.181E-18 4.269E-18 1.597E-18
**** TRANSISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT 0:Q1
RB 5.734E-18
RC 0.
RE 0.
IB 6.073E-19
IC 3.307E-17
FE 0.
TOTAL 3.941E-17
**** MOSFET SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT 0:M1
RD 0.
RS 0.
ID 1.401E-18
RX 1.462E+02
FE 0.
TOTAL 1.401E-18
**** TOTAL OUTPUT NOISE VOLTAGE = 4.786E-17 SQ V/HZ
= 6.918E-09 V/RT HZ

TRANSFER FUNCTION VALUE:
V(5)/VI = 1.351E+00
EQUIVALENT INPUT NOISE AT VI = 5.119E-09 /RT HZ
***** FREQ=7.5GHZ EQUIVALENT INPUT NOISE VOLTAGE=2.62E-17 SQ V/HZ
***** (DOUBLE THE INPUT NOISE AT LOW FREQ)

BICMOS DARLINGTON
VCC 1 0 5V
M1 1 2 3 0 NMOS W=100U L=1U
R1 3 0 300
Q1 5 3 4 NPN
R2 4 0 100
R3 1 5 2K
VI 7 0 2.5646V
*****
* USE INDUCTOR TO ALLOW VI TO SET DC BIAS.
* BUT CHOOSE A LARGE INDUCTOR TO GET VERY LARGE IMPEDANCE
* AT 7.5GIGAHERTZ.
*****
LBIAS 2 7 1KHENRY
IS 2 0 0A AC 1
.NOISE V(5) IS 10
.AC DEC 80 10MEG LOGIG
.MODEL NPN NPN BF=100 RB=100 IS=1E-16 CJE=330FF CJC=50FF
.MODEL NMOS NMOS KP=60U VTO=0.7V TOX=153E-10 CBS=50FF
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.PROBE
.END

***** OPERATING POINT INFORMATION          THOM= 27.000 TEMP= 27.000

+0:1 = 5.000E+00 0:2 = 2.564E+00 0:3 = 8.762E-01
+0:4 = 1.010E-01 0:5 = 2.999E+00 0:7 = 2.564E+00

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT 0:Q1
MODEL 0:NPN
IB 1.000E-05
IC 1.000E-03
VBE 7.752E-01

```

```

VCE 2.898E+00
VBC -2.123E+00
VS -2.999E+00
POWER 2.907E-03
BETAD 1.000E+02
GM 3.867E-02
RPI 2.586E+03
RX 1.000E+02
RO 2.124E+16
CPI 5.605E-13
CMU 3.209E-14
CBX 0.
CCS 0.
BETAAC 9.999E+01
FT 1.038E+10

```

**** MOSFETS

```

ELEMENT 0:M1
MODEL 0:NMOS
ID 2.931E-03
IBS -8.762E-15
IBD -5.000E-14
VGS 1.688E+00
VDS 4.123E+00
VBS -8.762E-01
VTH 7.000E-01
VDSAT 9.884E-01
BETA 6.000E-03
GAM EFF 0.
GM 5.930E-03
GDS 0.
GMB 0.
COTOT 1.241E-15
COTOT 1.549E-13
CSTOT 1.850E-13
CSTOT 3.772E-14
CGS 1.505E-13
CGD 1.241E-15

```

```
***** NOISE ANALYSIS          THOM= 27.000 TEMP= 27.000
```

```

FREQUENCY = 9.999E+06 HZ
**** TOTAL OUTPUT NOISE VOLTAGE = 3.361E-15 SQ V/HZ
= 5.797E-08 V/RT HZ

```

```

TRANSFER FUNCTION VALUE:
V(5)/IS = 2.661E+06
EQUIVALENT INPUT NOISE AT IS = 2.178E-14 /RT HZ

```

```

FREQUENCY = 9.999E+08 HZ
**** TOTAL OUTPUT NOISE VOLTAGE = 7.214E-16 SQ V/HZ
= 2.686E-08 V/RT HZ

```

```

TRANSFER FUNCTION VALUE:
V(5)/IS = 1.217E+04
EQUIVALENT INPUT NOISE AT IS = 2.206E-12 /RT HZ

```

```

FREQUENCY = 7.498E+09 HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT 0:R1 0:R2 0:R3
TOTAL 4.416E-18 1.802E-18 1.414E-18
**** TRANSISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT 0:Q1

```

```

RB 2.069E-18
RC 0.
RE 0.
IB 6.156E-19
IC 3.315E-17
FE 0.

```

```

TOTAL 3.584E-17
**** MOSFET SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT 0:M1

```

```

RD 0.
RS 0.
ID 5.237E-18
RX 2.827E+02
FE 0.

```

```

TOTAL 5.237E-18
**** TOTAL OUTPUT NOISE VOLTAGE = 4.871E-17 SQ V/HZ
= 6.979E-09 V/RT HZ

```

```

TRANSFER FUNCTION VALUE:
V(5)/IS = 3.580E+02
EQUIVALENT INPUT NOISE AT IS = 1.949E-11 /RT HZ

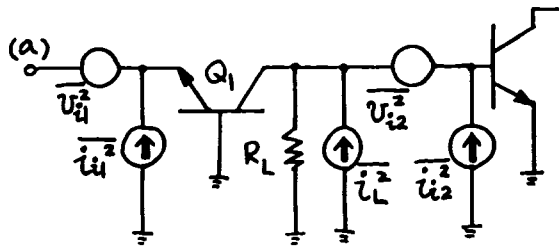
```

```

FREQ=7.5GHZ
EQUIVALENT INPUT NOISE CURRENT=3.8E-22 SQ A/HZ

```

11.10

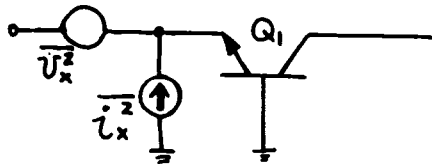


$\overline{U_{i2}^2}$ negligible.

$$\frac{\overline{i_{i1}^2}}{\Delta f} = 2q(I_{B1} + \frac{I_{C1}}{|\beta_1|^2})$$

$$\frac{\overline{i_{i2}^2}}{\Delta f} = 2q(I_{B2} + \frac{I_{C2}}{|\beta_2|^2})$$

Represent total noise by



Open circuit input and equate output noise, ($\alpha_1 \approx 1$)

$$\overline{i_x^2} = \overline{i_{i1}^2} + \overline{i_{i2}^2} + \overline{i_L^2}$$

$$\begin{aligned} \therefore \frac{\overline{i_x^2}}{\Delta f} &= 2 \times 2q(I_B + \frac{I_C}{|\beta|^2}) + 4kT \frac{1}{R_L} \\ &= 4 \times 1.6 \times 10^{-19} \left(10^{-5} + \frac{10^{-3}}{10^4} (1 + 10^4 \frac{f^2}{f_T^2}) \right) \\ &\quad + 1.66 \times 10^{-20} \times \frac{1}{5000} \\ &= 9.7 \times 10^{-24} + 6.4 \times 10^{-22} \left(\frac{f}{f_T} \right)^2 \end{aligned}$$

Short circuit input and equate output noise

$$g_m U_x = g_m U_{i1} + i_L + i_{i2}$$

$$\therefore \overline{U_x^2} = \overline{U_{i1}^2} + \frac{\overline{i_L^2}}{g_m^2} + \frac{\overline{i_{i2}^2}}{g_m^2}$$

$$\begin{aligned} \therefore \frac{\overline{U_x^2}}{\Delta f} &= 4kT \frac{1}{2g_m} + 4kT \frac{1}{g_m} \frac{1}{g_m R_L} \\ &\quad + \frac{1}{g_m^2} \times 2q(I_{B2} + \frac{I_{C2}}{|\beta|^2}) \\ &\approx 4kT \frac{1}{2g_m} \\ &= 1.66 \times 10^{-20} \times 13 \\ &= 2.2 \times 10^{-19} \text{ V}^2/\text{Hz} \end{aligned}$$

(b) With $R_s = 5k\Omega$, $\overline{U_{i1}^2}$ is negligible.

Total input current noise is

$$\overline{i_y^2} = \overline{i_x^2} + 4kT \frac{1}{R_s} \Delta f$$

$$\begin{aligned} \therefore \frac{\overline{i_y^2}}{\Delta f} &= 9.7 \times 10^{-24} + 6.4 \times 10^{-22} \left(\frac{f}{f_T} \right)^2 \\ &\quad + 1.66 \times 10^{-20} \times \frac{1}{5000} \\ &= 13 \times 10^{-24} + 6.4 \times 10^{-22} \left(\frac{f}{f_T} \right)^2 \end{aligned}$$

Total current noise

$$\overline{i_T^2} = \int_0^{f_1} \left[13 \times 10^{-24} + 6.4 \times 10^{-22} \left(\frac{f}{f_T} \right)^2 \right] df$$

$$f_1 = 150 \text{ MHz}$$

$$\begin{aligned} \overline{i_T^2} &= 13 \times 10^{-24} \times 150 \times 10^6 + 6.4 \times 10^{-22} \frac{f_1^3}{f_T^2 \cdot 3} \\ &= 1.95 \times 10^{-15} + 4.5 \times 10^{-15} \\ &= 6.45 \times 10^{-15} \text{ A}^2 \end{aligned}$$

$$\therefore i_T = 80 \text{ nA rms}$$

$$\therefore \text{for } 10\text{dB } S/N \quad i_s = 253 \text{ nA}$$

11-12

LOW-INPUT-IMPEDANCE COMMON BASE AMP

```
Q1 2 0 3 NPN
Q2 1 2 0 NPN
VCC 1 0 5.82629V
R1 1 2 5K
VI 3 0 -0.774219V AC 1
.NOISE V(2) VI 10
.AC DEC 10 10K 10HGS
*****
```

* ADJUST TF AND CJE TO GET THE SPECIFIED FT=400MEGAHERTZ

```
.MODEL NPN NPN BF=100 IS=1E-16 CJE=900FF TF=358PS
.WIDTH OUT=80
.OPTIONS SPICE NOMOD
.OP
.END
```

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

+0:1 = 5.826E+00 0:2 = 7.742E-01 0:3 = -7.742E-01

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	0:Q1	0:Q2
MODEL	0:NPN	0:NPN
IS	1.000E-05	1.000E-05
IC	1.000E-03	1.000E-03
VBE	7.742E-01	7.742E-01
VCE	1.548E+00	5.826E+00
VBC	-7.742E-01	-5.052E+00
VS	-7.742E-01	-5.826E+00
POWER	1.557E-03	5.836E-03
BETAD	1.000E+02	1.000E+02
GM	3.868E-02	3.868E-02
RPI	2.585E+03	2.585E+03
RX	0.	0.
RO	7.742E+15	5.052E+16
CPI	1.538E-11	1.538E-11
CNU	0.	0.
CEX	0.	0.
CCS	0.	0.
BETAMC	9.999E+01	9.999E+01
FT	4.003E+08	4.003E+08

***** NOISE ANALYSIS THOM= 27.000 TEMP= 27.000

FREQUENCY = 9.999E+03 HZ
**** TOTAL OUTPUT NOISE VOLTAGE = 9.500E-16 SQ V/Hz
= 3.082E-08 V/RT HZ

TRANSFER FUNCTION VALUE:
V(2)/VI = 6.591E+01
EQUIVALENT INPUT NOISE AT VI = 4.676E-10 /RT HZ

FREQUENCY = 9.999E+04 HZ
**** TOTAL OUTPUT NOISE VOLTAGE = 9.498E-16 SQ V/Hz
= 3.082E-08 V/RT HZ

TRANSFER FUNCTION VALUE:
V(2)/VI = 6.591E+01
EQUIVALENT INPUT NOISE AT VI = 4.676E-10 /RT HZ

FREQUENCY = 1.000E+06 HZ
**** TOTAL OUTPUT NOISE VOLTAGE = 9.250E-16 SQ V/Hz
= 3.041E-08 V/RT HZ

TRANSFER FUNCTION VALUE:
V(2)/VI = 6.504E+01
EQUIVALENT INPUT NOISE AT VI = 4.676E-10 /RT HZ

FREQUENCY = 9.999E+06 HZ
**** TOTAL OUTPUT NOISE VOLTAGE = 2.560E-16 SQ V/Hz
= 1.600E-08 V/RT HZ

TRANSFER FUNCTION VALUE:
V(2)/VI = 3.422E+01
EQUIVALENT INPUT NOISE AT VI = 4.676E-10 /RT HZ

EQUIVALENT INPUT NOISE VOLTAGE = 2.186E-19 SQ V/Hz

LOW-INPUT-IMPEDANCE COMMON BASE AMP

```
Q1 2 0 3 NPN
Q2 1 2 0 NPN
VCC 1 0 5.82629V
R1 1 2 5K
*****
```

* USE INDUCTOR TO ALLOW VI TO SET DC BIAS.
* CHOOSE A LARGE INDUCTANCE TO GET VERY LARGE IMPEDANCE.

```
LSIAS 3 7 1GIGHENRY
VI 7 0 -0.774219V
IS 3 0 0A AC 1
.NOISE V(2) IS 10
.AC DEC 10 100K 1GIG
.MODEL NPN NPN BF=100 IS=1E-16 CJE=900FF TF=358PS
.WIDTH OUT=80
.OPTIONS SPICE NOMOD
.OP
.END
```

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

+0:1 = 5.826E+00 0:2 = 7.742E-01 0:3 = -7.742E-01
+0:7 = -7.742E-01

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	0:Q1	0:Q2
MODEL	0:NPN	0:NPN
IS	1.000E-05	1.000E-05
IC	1.000E-03	1.000E-03
VBE	7.742E-01	7.742E-01
VCE	1.548E+00	5.826E+00
VBC	-7.742E-01	-5.052E+00
VS	-7.742E-01	-5.826E+00
POWER	1.557E-03	5.836E-03
BETAD	1.000E+02	1.000E+02
GM	3.868E-02	3.868E-02
RPI	2.585E+03	2.585E+03
RX	0.	0.
RO	7.742E+15	5.052E+16
CPI	1.538E-11	1.538E-11
CNU	0.	0.
CEX	0.	0.
CCS	0.	0.
BETAMC	9.999E+01	9.999E+01
FT	4.003E+08	4.003E+08

BY HAND ANALYSIS, EQUIVALENT INPUT NOISE CURRENT =
 $9.7E-24 + 6.4E-22(F/FT)^2 \text{ SQ A / Hz}$

FREQUENCY = 9.999E+04 HZ
EQUIVALENT INPUT NOISE AT IS = 3.145E-12 /RT HZ
BY HAND 3.11E-12 A /RT HZ

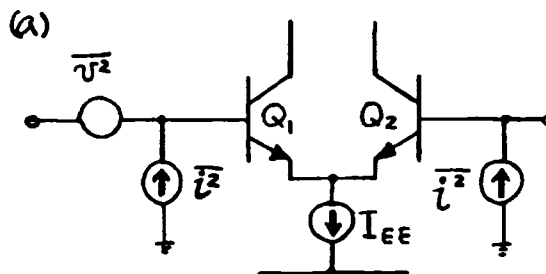
FREQUENCY = 1.000E+06 HZ
EQUIVALENT INPUT NOISE AT IS = 3.145E-12 /RT HZ
BY HAND 3.12E-12 A /RT HZ

FREQUENCY = 9.999E+06 HZ
EQUIVALENT INPUT NOISE AT IS = 3.177E-12 /RT HZ
BY HAND 3.18E-12 A /RT HZ

FREQUENCY = 9.999E+07 HZ
EQUIVALENT INPUT NOISE AT IS = 5.504E-12 /RT HZ
BY HAND 7.05E-12 A /RT HZ

FREQUENCY = 9.999E+08 HZ
EQUIVALENT INPUT NOISE AT IS = 4.528E-11 /RT HZ
BY HAND 6.33E-11 A /RT HZ

11.11



$$\overline{V^2} = 4kT(2r_b + \frac{1}{g_{m1}}) \Delta f$$

$$\therefore \frac{\overline{V^2}}{\Delta f} = 1.66 \times 10^{-20} (1000 + 52k)$$

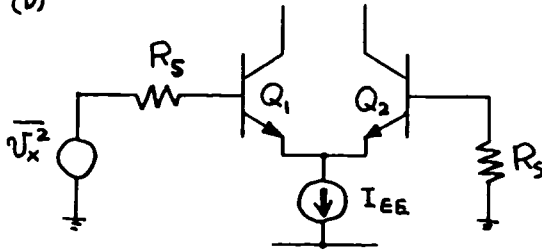
$$= 8.8 \times 10^{-16} \text{ V}^2/\text{Hz}$$

$$\frac{\overline{i^2}}{\Delta f} = 2g_{I_B} = 3.2 \times 10^{-19} \times \frac{0.5 \times 10^{-6}}{5000}$$

$$= 3.2 \times 10^{-29} \text{ A}^2/\text{Hz}$$

11-13

(b)

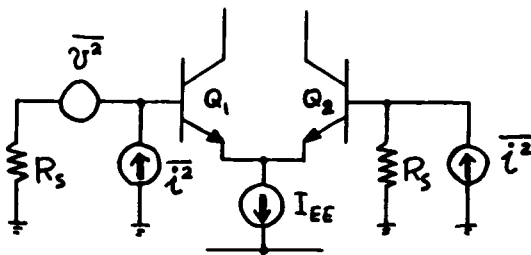


Make $\overline{v_x^2}$ equiv. to noise of the circuit.

At the base of Q_1 this produces a voltage

$$\overline{v_{ix}^2} = \left(\frac{R_i}{R_i + R_S} \right)^2 \overline{v_x^2} \text{ ----- (A)}$$

where R_i is resistance seen looking in at the base of Q_1



Include noise due to R_S in $\overline{i^2}$
At the base of Q_1

$$v_1 = v \frac{R_i}{R_i + R_S} + i \frac{R_S R_i}{R_i + R_S}$$

At the base of Q_2

$$v_2 = i \frac{R_S R_i}{R_i + R_S}$$

Thus total input noise voltage is

$$\overline{v_1^2} + \overline{v_2^2} = \overline{v^2} \left(\frac{R_i}{R_i + R_S} \right)^2 + 2 \overline{i^2} \frac{R_i^2 R_S^2}{(R_i + R_S)^2}$$

Equate to $\overline{v_{ix}^2}$ in (A)

$$\therefore \overline{v_x^2} = \overline{v^2} + 2 \overline{i^2} R_S^2$$

Include noise due to i_s in $\overline{i^2}$

$$\begin{aligned} \therefore \frac{\overline{i^2}}{\Delta f} &= 2qI_B + 4kT \frac{1}{R_S} \\ &= 3.2 \times 10^{-29} + 1.66 \times 10^{-20} \frac{1}{10^8} \\ &= 19.8 \times 10^{-29} \text{ A}^2/\text{Hz} \end{aligned}$$

$$\begin{aligned} \therefore \frac{\overline{v_x^2}}{\Delta f} &= 8.8 \times 10^{-16} + 2 \times 19.8 \times 10^{-29} \times 10^6 \\ &= 3.96 \times 10^{-12} \text{ V}^2/\text{Hz} \end{aligned}$$

$\therefore$ Total input noise with
 $\Delta f = 1 \text{ KHz}$

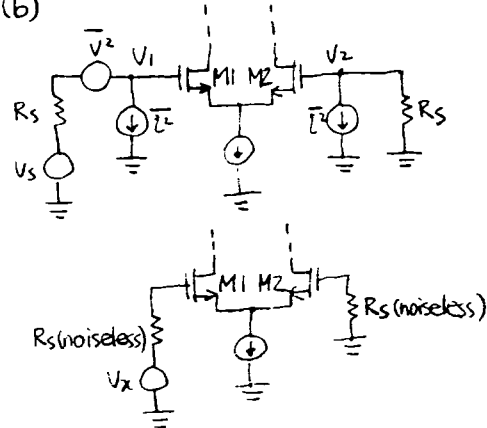
$$\begin{aligned} \overline{v_T^2} &= 3.96 \times 10^{-12} \times 1000 \\ &= 3.96 \times 10^{-9} \text{ V}^2 \end{aligned}$$

$$\therefore v_T = 63 \mu\text{V rms}$$

11.12

$$\begin{aligned} \text{(a)} \frac{\overline{v^2}}{\Delta f} &= 2 \times 4kT \frac{2}{3} \frac{1}{g_m} \\ &= 2 \times 4 \times 1.38 \times 10^{-23} \times 300 \times \frac{2}{3} \times \frac{1}{0.5 \times 10^{-3}} \\ &= 4.4 \times 10^{-17} \text{ V}^2/\text{Hz} \\ \frac{\overline{i^2}}{\Delta f} &= 2qI_G = 2 \times 1.6 \times 10^{-19} \times 0.1 \times 10^{-15} \\ &= 3.2 \times 10^{-35} \text{ A}^2/\text{Hz} \end{aligned}$$

(b)



11-14

The noise voltage at the gate of M1

$$V_1 = U + iR_s$$

At the gate of M2

$$V_2 = iR_s$$

$$\overline{V_1^2} + \overline{V_2^2} = \overline{U^2} + 2\overline{i^2}R_s^2$$

$\overline{U^2}$ is the same as previous, and $\overline{i^2}$ also includes the contribution of R_s

$$\begin{aligned}\frac{\overline{i^2}}{\Delta f} &= 2qI_G + 4kT \frac{1}{R_s} \\ &= 3.2 \times 10^{-35} + 4 \times 1.38 \times 10^{-23} \times 300 \times \frac{1}{100 \times 10^6} \\ &= 3.2 \times 10^{-35} + 1.6 \times 10^{-28} \\ &= 1.2 \times 10^{-28} \text{ A}^2/\text{Hz}\end{aligned}$$

If V_x is placed at R_s to give the same noise, its only contribution at the gate of M1 is

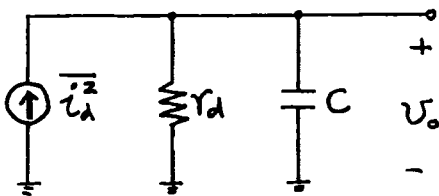
$$\overline{V_{V_x}^2} = \overline{U^2}$$

$$\begin{aligned}\frac{\overline{V_x^2}}{\Delta f} &= \frac{\overline{U^2}}{\Delta f} + \frac{\overline{V_2^2}}{\Delta f} \\ &= \frac{\overline{U^2}}{\Delta f} + 2 \frac{\overline{i^2}}{\Delta f} R_s^2 \\ &= 4.4 \times 10^{-17} + 2 \times 1.6 \times 10^{-28} \times (100 \times 10^6)^2 \\ &= 4.4 \times 10^{-17} + 3.2 \times 10^{-12} \\ &= 3.2 \times 10^{-12} \text{ V}^2/\text{Hz}\end{aligned}$$

$$V_T^2 = 3.2 \times 10^{-12} \times 10^3 = 3.2 \times 10^{-9} \text{ V}^2$$

$$V_T = 5.6 \times 10^{-5} \text{ V} = 56 \mu\text{V}$$

11.13



Neglect noise in R

$$r_d = 55.3 \Omega, C = 100 \text{ pF}$$

Noise bandwidth

$$= \frac{\pi}{2} \frac{1}{2\pi r_d C} = \frac{\pi}{2} \frac{1}{2\pi \times 55.3 \times 10^{-10}}$$

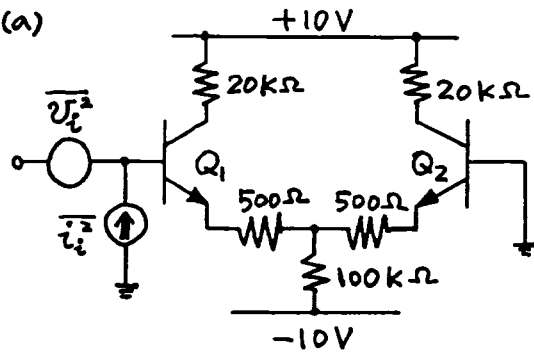
$$\therefore f_N = 45.2 \text{ MHz}$$

$\therefore$ Total output noise is

$$\begin{aligned}\overline{V_{OT}^2} &= \frac{\overline{i_n^2}}{\Delta f} \times r_d^2 \times f_N \\ &= 3060 \times 1.51 \times 10^{-22} \times 45.2 \times 10^6 \\ &= 2.1 \times 10^{-11} \text{ V}^2\end{aligned}$$

$$\therefore V_{OT} = 4.6 \mu\text{V rms}$$

11.14



$$I_{C1} = \frac{1}{2} \frac{9.4}{100k} = 47 \mu\text{A}$$

Neglect noise due to R_L

$$\overline{V_i^2} = 4kT(2r_b + \frac{1}{g_{m1}} + 2R_E) \Delta f$$

$$\begin{aligned}\therefore \frac{\overline{V_i^2}}{\Delta f} &= 1.66 \times 10^{-20} (400 + 553 + 1000) \\ &= 3.24 \times 10^{-17} \text{ V}^2/\text{Hz}\end{aligned}$$

$$\overline{i_i^2} = 2qI_B \Delta f$$

$$\begin{aligned}\therefore \frac{\overline{i_i^2}}{\Delta f} &= 3.2 \times 10^{-19} \times \frac{47 \times 10^{-6}}{100} \\ &= 1.5 \times 10^{-25} \text{ A}^2/\text{Hz}\end{aligned}$$

(b) Since $R_s = 50 \Omega$, neglect $\overline{i_i^2}$

Total input noise voltage

$$\begin{aligned}\overline{V_{iT}^2} &= 3.24 \times 10^{-17} \times 30 \times 10^6 \times \frac{\pi}{2} \\ &= 1.53 \times 10^{-9} \text{ V}^2\end{aligned}$$

$$\therefore V_{iT} = 39.1 \mu\text{V rms}$$

Gain

$$\frac{V_o}{V_s} = \frac{g_{m1}}{1 + g_{m1}R_E} R_L$$

$$= \frac{0.047}{26} \frac{1}{1 + \frac{0.047}{26} \times 500} \times 20,000$$

$$= 19$$

$\therefore$ Output noise voltage

$$V_{OT} = 19 \times 39.1 = 743 \mu\text{V rms}$$

11-15

DIFFERENTIAL INPUT STAGE

```

RC1 1 5 20K
RC2 1 6 20K
Q1 5 3 7 NPN
Q2 6 0 8 NPN
RE1 7 9 500
RE2 8 9 500
RRE 9 2 100K
VCC 1 0 10V
VEE 2 0 -10V
VI 3 0 0V AC 1
.NOISE V(5,6) VI 10
.AC DEC 10 100K 100MEG
.MODEL NPN NPN BF=100 RB=200
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.PROBE
.END

```

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

```

+0:1 = 1.000E+01 0:2 = -1.000E+01 0:3 = 0.
+0:5 = 9.081E+00 0:6 = 9.081E+00 0:7 = -6.946E-01
+0:8 = -6.946E-01 0:9 = -7.178E-01

```

**** BIPOLAR JUNCTION TRANSISTORS

```

ELEMENT 0:Q1 0:Q2
MODEL 0:NPN 0:NPN
IB 4.595E-07 4.595E-07
IC 4.595E-05 4.595E-05
VBE 6.946E-01 6.946E-01
VCE 9.775E+00 9.775E+00
VBC -9.081E+00 -9.081E+00
VS -9.081E+00 -9.081E+00
POWER 4.495E-04 4.495E-04
BETAD 1.000E+02 1.000E+02
GM 1.777E-03 1.777E-03
RPI 5.628E+04 5.628E+04
RK 2.000E+02 2.000E+02
RO 9.081E+16 9.081E+16
CPI 0. 0.
CMU 0. 0.
CBX 0. 0.
CCS 0. 0.
BETAAC 9.999E+01 9.999E+01
FT 2.827E+11 2.827E+11

```

***** NOISE ANALYSIS THOM= 27.000 TEMP= 27.000

```

FREQUENCY = 9.999E+04 HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT 0:RC1 0:RC2 0:RE1 0:RE2 0:REE
TOTAL 3.315E-16 3.315E-16 2.896E-15 2.896E-15 0.
**** TRANSISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT 0:Q1 0:Q2
RB 1.159E-15 1.159E-15
RC 0. 0.
RE 0. 0.
IB 2.521E-17 2.521E-17
IC 1.671E-15 1.671E-15
FW 0. 0.
TOTAL 2.855E-15 2.855E-15
**** TOTAL OUTPUT NOISE VOLTAGE = 1.217E-14 SQ V/HZ
= 1.103E-07 V/RT HZ

```

TRANSFER FUNCTION VALUE:

V(5,6)/VI = 1.869E+01

EQUIVALENT INPUT NOISE AT VI = 5.900E-09 /RT HZ

FREQUENCY = 1.000E+06 HZ
EQUIVALENT INPUT NOISE AT VI = 5.900E-09 /RT HZ

FREQUENCY = 9.999E+06 HZ
EQUIVALENT INPUT NOISE AT VI = 5.900E-09 /RT HZ

FREQUENCY = 9.999E+07 HZ
EQUIVALENT INPUT NOISE AT VI = 5.900E-09 /RT HZ

EQUIVALENT INPUT NOISE VOLTAGE = 3.48E-17 SQ V/HZ

DIFFERENTIAL INPUT STAGE

```

RC1 1 5 20K
RC2 1 6 20K
Q1 5 3 7 NPN
Q2 6 0 8 NPN
RE1 7 9 500
RE2 8 9 500
RRE 9 2 100K
VCC 1 0 10V
VEE 2 0 -10V
LBIAS 3 0 1GIGHENRY
IS 3 0 0A AC 1
.NOISE V(5,6) IS 10
.AC DEC 10 100K 100MEG
.MODEL NPN NPN BF=100 RB=200
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80

```

.OPTIONS SPICE

```

.OP
.PROBE
.END

```

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

```

+0:1 = 1.000E+01 0:2 = -1.000E+01 0:3 = 0.
+0:5 = 9.081E+00 0:6 = 9.081E+00 0:7 = -6.946E-01
+0:8 = -6.946E-01 0:9 = -7.178E-01

```

**** BIPOLAR JUNCTION TRANSISTORS

```

ELEMENT 0:Q1 0:Q2
MODEL 0:NPN 0:NPN
IB 4.595E-07 4.595E-07
IC 4.595E-05 4.595E-05
VBE 6.946E-01 6.946E-01
VCE 9.775E+00 9.775E+00
VBC -9.081E+00 -9.081E+00
VS -9.081E+00 -9.081E+00
POWER 4.495E-04 4.495E-04
BETAD 1.000E+02 1.000E+02
GM 1.777E-03 1.777E-03
RPI 5.628E+04 5.628E+04
RK 2.000E+02 2.000E+02
RO 9.081E+16 9.081E+16
CPI 0. 0.
CMU 0. 0.
CBX 0. 0.
CCS 0. 0.
BETAAC 9.999E+01 9.999E+01
FT 2.827E+11 2.827E+11

```

FREQUENCY = 9.999E+04 HZ

```

**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT 0:RC1 0:RC2 0:RE1 0:RE2 0:REE
TOTAL 3.315E-16 3.315E-16 0. 3.182E-19 6.364E-17

```

**** TRANSISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)

```

ELEMENT 0:Q1 0:Q2
RB 0. 1.273E-19
RC 0. 0.
RE 0. 0.
IB 2.308E-12 5.733E-17
IC 2.308E-14 1.393E-18
FW 0. 0.
TOTAL 2.331E-12 5.885E-17

```

**** TOTAL OUTPUT NOISE VOLTAGE = 2.332E-12 SQ V/HZ
= 1.527E-06 V/RT HZ

TRANSFER FUNCTION VALUE:

V(5,6)/IS = 3.979E+06
EQUIVALENT INPUT NOISE AT IS = 3.838E-13 /RT HZ

FREQUENCY = 1.000E+06 HZ
EQUIVALENT INPUT NOISE AT IS = 3.838E-13 /RT HZ

FREQUENCY = 9.999E+06 HZ
EQUIVALENT INPUT NOISE AT IS = 3.838E-13 /RT HZ

FREQUENCY = 9.999E+07 HZ
EQUIVALENT INPUT NOISE AT IS = 3.838E-13 /RT HZ

EQUIVALENT INPUT NOISE CURRENT = 1.47E-25 SQ A/HZ

11.15

$$(a) \frac{\overline{V_i^2}}{\Delta f} = 4kT(r_b + \frac{1}{2g_m})$$

$$= 1.66 \times 10^{-20} (100 + 6.5)$$

$$= 1.77 \times 10^{-18} \frac{V^2}{Hz}$$

$$\frac{\overline{i_i^2}}{\Delta f} = 2qI_B = 3.2 \times 10^{-19} \times \frac{2 \times 10^{-3}}{50}$$

$$= 1.28 \times 10^{-23} \frac{A^2}{Hz}$$

$$R_{s_{opt}}^2 = \frac{1.77 \times 10^{-18}}{1.28 \times 10^{-23}} = 1.38 \times 10^5 \Omega^2$$

$$R_{s_{opt}} = 372 \Omega$$

$$F_{opt} = 1 + \frac{1}{\sqrt{\beta}} \sqrt{1 + 2g_m r_b}$$

$$= 1 + \frac{1}{\sqrt{50}} \sqrt{1 + 2 \frac{100}{13}}$$

$$= 1.57 = 1.97 \text{ dB}$$

$$(b) R_{s_{opt}} = \frac{\sqrt{\beta}}{g_m} \sqrt{1 + 2g_m r_b}$$

$$= 10(2600) \sqrt{1 + 2 \frac{300}{2600}}$$

$$= 28.8 \text{ k}\Omega$$

$$F_{opt} = 1 + \frac{1}{10} \sqrt{1 + 2 \frac{300}{2600}}$$

$$= 1.111 = 0.46 \text{ dB}$$

11.16

(a) From 11.15

$$\frac{\overline{V_i^2}}{\Delta f} = 1.77 \times 10^{-18} \frac{V^2}{Hz}$$

$$\frac{\overline{i_i^2}}{\Delta f} = 2qI_B + \frac{K}{f}$$

$$2qI_B = \frac{K}{f} \text{ at } f = 10^3 \text{ Hz}$$

$$K = 2qI_B 10^3$$

$$\frac{\overline{i_i^2}}{\Delta f} = 2qI_B (1 + \frac{10^3}{f})$$

at 500 Hz

$$\frac{\overline{i_i^2}}{\Delta f} = 3.2 \times 10^{-19} \left(\frac{2 \times 10^{-3}}{50} \right) (3)$$

$$= 3.84 \times 10^{-23} \frac{A^2}{Hz}$$

11-16

$$R_{s_{opt}}^2 = \frac{1.77 \times 10^{-18}}{3.84 \times 10^{-23}}$$

$$R_{s_{opt}} = 215 \Omega$$

$$F_{opt} = 1 + \frac{\overline{V_i^2}}{4kT R_{s_{opt}} \Delta f} + \frac{\overline{i_i^2}}{4kT \frac{1}{R_{s_{opt}}} \Delta f}$$

$$= 1 + \frac{1.77 \times 10^{-18}}{1.66 \times 10^{-20} \times 215} + \frac{3.84 \times 10^{-23}}{1.66 \times 10^{-20} \times \frac{1}{215}}$$

$$= 1 + 0.496 + 0.496$$

$$= 1.992 = 3 \text{ dB}$$

$$(b) \frac{\overline{V_i^2}}{\Delta f} = 4kT(r_b + \frac{1}{2g_m})$$

$$= 1.66 \times 10^{-20} (300 + 1300)$$

$$= 2.66 \times 10^{-17} \frac{V^2}{Hz}$$

$$\frac{\overline{i_i^2}}{\Delta f} = 2qI_B + \frac{K}{f}$$

$$= 2qI_B (1 + \frac{1000}{f})$$

At 500 Hz

$$\frac{\overline{i_i^2}}{\Delta f} = 3.2 \times 10^{-19} \times \frac{10 \times 10^{-6}}{100} \times 3$$

$$= 9.6 \times 10^{-26} \frac{A^2}{Hz}$$

$$\therefore R_{s_{opt}}^2 = \frac{2.66 \times 10^{-17}}{9.6 \times 10^{-26}}$$

$$\therefore R_{s_{opt}} = 16.6 \text{ k}\Omega$$

$$F_{opt} = 1 + 2 \times \frac{2.66 \times 10^{-17}}{1.66 \times 10^{-20} \times 16600}$$

$$= 1.193 = 0.77 \text{ dB}$$

11.17

The emitter resistor can be added to r_b and (11.146) and (11.147) can be used

$$(a) R_{s_{opt}} = \sqrt{50 \times 13} \sqrt{1 + 2 \frac{1100}{13}}$$

$$= 1200 \Omega$$

$$F_{opt} = 1 + \frac{1}{\sqrt{50}} \sqrt{1 + 2 \frac{1100}{13}}$$

$$= 2.85 = 4.54 \text{ dB}$$

11-17

$$\begin{aligned} (b) R_{s \text{ opt}} &= \sqrt{100} \times 2600 \sqrt{1 + 2 \frac{1300}{2600}} \\ &= 36.8 \text{ k}\Omega \\ F_{\text{opt}} &= 1 + \frac{1}{10} \sqrt{1 + 2 \frac{1300}{2600}} \\ &= 1.14 = 0.57 \text{ dB} \end{aligned}$$

11.18

(a) Equivalent input noise generators for the differential pair

$$\begin{aligned} \frac{\overline{v_i^2}}{\Delta f} &= 4kT(2r_b + \frac{1}{g_m} + 2R_E) \\ &= 3.24 \times 10^{-17} \text{ V}^2/\text{Hz} \\ &\quad \text{from 11.13} \end{aligned}$$

$$\begin{aligned} \frac{\overline{i_i^2}}{\Delta f} &= 1.5 \times 10^{-25} \text{ A}^2/\text{Hz} \\ F &= 1 + \frac{\overline{v_i^2}}{4kTR_s \Delta f} + \frac{\overline{i_i^2}}{4kT \frac{1}{R_s} \Delta f} \\ &= 1 + \frac{3.24 \times 10^{-17}}{1.66 \times 10^{-20} \times 50} + \frac{1.5 \times 10^{-25}}{1.66 \times 10^{-20} \times \frac{1}{50}} \\ &= 1 + 39.0 + 0 \\ &= 40 = 16 \text{ dB} \end{aligned}$$

$$(b) R_{s \text{ opt}}^2 = \frac{\overline{v_i^2}}{\overline{i_i^2}} = \frac{3.24 \times 10^{-17}}{1.5 \times 10^{-25}}$$

$$\therefore R_{s \text{ opt}} = 14.7 \text{ k}\Omega$$

Obviously NF decreases for $R_s = 100\Omega$, because we move closer to $R_{s \text{ opt}}$.

$R_s = 200\text{k}\Omega$ is larger than $R_{s \text{ opt}}$ but only 14x. This is closer to $R_{s \text{ opt}}$ than 50Ω and thus NF for $R_s = 200\text{k}$ will be lower than for $R_s = 50\Omega$

$$\begin{aligned} (c) \frac{\overline{v_i^2}}{\Delta f} &= 3.24 \times 10^{-17} \text{ V}^2/\text{Hz} \\ \frac{\overline{i_i^2}}{\Delta f} &= 1.5 \times 10^{-25} (1 + \frac{10000}{f}) \text{ A}^2/\text{Hz} \\ F &= 1 + \frac{\overline{v_i^2}}{4kTR_s \Delta f} + \frac{\overline{i_i^2}}{4kT \frac{1}{R_s} \Delta f} \\ &= 1 + \frac{3.24 \times 10^{-17}}{1.66 \times 10^{-20} \times 2 \times 10^5} + \frac{1.5 \times 10^{-25} (1 + \frac{10000}{f})}{1.66 \times 10^{-20} \times \frac{1}{2 \times 10^5}} \\ &= 1 + 9.8 \times 10^{-3} + 1.8 (1 + \frac{10000}{f}) \\ &= 1.01 + 1.8 + \frac{18000}{f} \\ \text{Put } F &= 100 \text{ (20dB)} \\ \therefore f &= 185 \text{ Hz} \end{aligned}$$

11.19

(a) Neglect effect of $10\text{k}\Omega$ load

$$\begin{aligned} \frac{\overline{v_i^2}}{\Delta f} &= 4kT(r_b + \frac{1}{g_m}) \\ &= 1.66 \times 10^{-20} (100 + 26) \\ &= 2.09 \times 10^{-18} \text{ V}^2/\text{Hz} \\ \frac{\overline{i_i^2}}{\Delta f} &= 2g I_B + 4kT \frac{1}{R_F} \\ &= 3.2 \times 10^{-19} \times \frac{500 \times 10^{-6}}{50} + 1.66 \times 10^{-20} \times \frac{1}{10^4} \\ &= 3.2 \times 10^{-24} + 1.66 \times 10^{-24} \\ &= 4.86 \times 10^{-24} \text{ A}^2/\text{Hz} \end{aligned}$$

$$\begin{aligned} F &= 1 + \frac{\overline{v_i^2}}{4kTR_s \Delta f} + \frac{\overline{i_i^2}}{4kT \frac{1}{R_s} \Delta f} \\ &= 1 + \frac{2.09 \times 10^{-18}}{1.66 \times 10^{-20} \times 10^4} + \frac{4.86 \times 10^{-24}}{1.66 \times 10^{-20} \times 10^{-4}} \\ &= 1 + 0.01 + 2.93 \\ &= 3.94 = 5.96 \text{ dB} \end{aligned}$$

$$\begin{aligned} (b) \frac{\overline{i_i^2}}{\Delta f} &= 2g(I_B + \frac{I_c}{|\beta|^2}) + 4kT \frac{1}{R_F} \\ &\approx 2g[I_B + I_c(\frac{f}{f_T})^2] + 4kT \frac{1}{R_F} \end{aligned}$$

$$\begin{aligned}\frac{\overline{i_x^2}}{\Delta f} &= 3.2 \times 10^{-24} \left[1 + \frac{I_c}{I_B} \left(\frac{f}{f_T} \right)^2 \right] + 1.66 \times 10^{-24} \\ &= 3.2 \times 10^{-24} \left[1 + 50 \left(\frac{f}{f_T} \right)^2 \right] + 1.66 \times 10^{-24}\end{aligned}$$

Put $F = 8.96 \text{ dB} = 7.87$

$$\therefore \frac{\overline{i_x^2}}{\Delta f} \times \frac{1}{4kT \frac{1}{R_s}} = F - 1.01 = 6.86$$

$$\therefore \frac{\overline{i_x^2}}{\Delta f} = 6.86 \times 1.66 \times 10^{-20} \times 10^{-4} = 1.14 \times 10^{-23}$$

$$\therefore 1.14 = 3.2 + 3.2 \times 50 \left(\frac{f}{f_T} \right)^2 + 1.66$$

$$\therefore f = 0.2 f_T = 100 \text{ MHz}$$

11.20

(a) From 11.10, the total input noise current is

$$\begin{aligned}\frac{\overline{i_x^2}}{\Delta f} &= 2 \times 2g I_B + 4kT \frac{1}{R_L} \\ &= 2 \times 3.2 \times 10^{-19} \times 10^{-5} + 1.66 \times 10^{-20} \times \frac{1}{5000} \\ &= 6.4 \times 10^{-24} + 3.32 \times 10^{-24} \\ &= 9.72 \times 10^{-24} \text{ A}^2/\text{Hz}\end{aligned}$$

$$\begin{aligned}\frac{\overline{v_i^2}}{\Delta f} &= 4kT \left(r_b + \frac{1}{2g_m} \right) \\ &= 1.66 \times 10^{-20} \times 13 = 2.16 \times 10^{-19} \text{ V}^2/\text{Hz}\end{aligned}$$

$$\begin{aligned}F &= 1 + \frac{\overline{v_i^2}}{4kT R_s \Delta f} + \frac{\overline{i_x^2}}{4kT \frac{1}{R_s} \Delta f} \\ &= 1 + \frac{2.16 \times 10^{-19}}{1.66 \times 10^{-20} \times 5000} + \frac{9.72 \times 10^{-24}}{1.66 \times 10^{-20} \times \frac{1}{5000}} \\ &= 1 + 0 + 2.93 = 3.93 = 5.94 \text{ dB}\end{aligned}$$

(b) Put $F = 8.94 \text{ dB} = 7.83$

$$\therefore \frac{\overline{i_x^2}}{4kT \frac{1}{R_s} \Delta f} = 6.83$$

$$\begin{aligned}\therefore \frac{\overline{i_x^2}}{\Delta f} &= 6.83 \times 1.66 \times 10^{-20} \times \frac{1}{5000} \\ &= 2.27 \times 10^{-23} \text{ A}^2/\text{Hz}\end{aligned}$$

With flicker noise

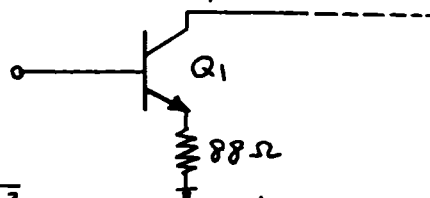
$$\begin{aligned}\frac{\overline{i_x^2}}{\Delta f} &= 2 \times 2g I_B \left(1 + \frac{1000}{f} \right) + 4kT \frac{1}{R_L} \\ &= 6.4 \times 10^{-24} \left(1 + \frac{1000}{f} \right) + 3.32 \times 10^{-24}\end{aligned}$$

$$\therefore 2.27 = 9.72 + \frac{6400}{f}$$

$$\therefore f = 493 \text{ Hz}$$

11.21

From the basic amplifier of Fig 8.21(b)



$$\frac{\overline{v_i^2}}{\Delta f} = 4kT \left(r_{b1} + \frac{1}{2g_{m1}} + R_{E1} \right)$$

$$I_{C1} = 0.58 \text{ mA}$$

$$\begin{aligned}\therefore \frac{\overline{v_i^2}}{\Delta f} &= 1.66 \times 10^{-20} (100 + 22 + 88) \\ &= 3.5 \times 10^{-18} \text{ V}^2/\text{Hz}\end{aligned}$$

For $R_s = 50 \Omega$, $\overline{i_x^2}$ is negligible as is the effect of $R_D = 12 \text{ k}\Omega$

$$\begin{aligned}\therefore \overline{v_{i_T}^2} &= 3.5 \times 10^{-18} \times 50 \times 10^6 \text{ V}^2 \\ &= 1.75 \times 10^{-10} \text{ V}^2\end{aligned}$$

$$\therefore v_{i_T} = 13.2 \mu\text{V rms}$$

From R_s

$$\begin{aligned}\frac{\overline{v_s^2}}{\Delta f} &= 4kT R_s = 1.66 \times 10^{-20} \times 50 \\ &= 8.3 \times 10^{-19} \text{ V}^2/\text{Hz}\end{aligned}$$

In 50 MHz

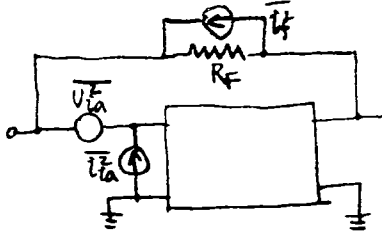
$$\begin{aligned}\frac{\overline{v_{s_T}^2}}{\Delta f} &= 8.3 \times 10^{-19} \times 50 \times 10^6 = 4.15 \times 10^{-11} \text{ V}^2 \\ \therefore F &= 1 + \frac{\overline{v_{i_T}^2}}{\overline{v_{s_T}^2}} = 1 + \frac{1.75 \times 10^{-10}}{4.15 \times 10^{-11}} = 5.22 \\ &= 7.17 \text{ dB}\end{aligned}$$

11.22

$$C_{ox} = \frac{\epsilon}{t_{ox}} = \frac{3.9 \times 8.85 \times 10^{-12}}{80 \times 10^{-10}} = 4.3 \times 10^{-3} \text{ F/m}^2$$

$$C_{gs} = \frac{2}{3} W L C_{ox} = \frac{2}{3} \times 100 \times 1 \times 10^{-12} \times 4.3 \times 10^{-3} = 2.9 \times 10^{-13} \text{ F}$$

$$g_m = \sqrt{2k'(W/L)I_D} = \sqrt{2 \times 194 \times 10^{-6} \times 100 \times 100 \times 10^{-6}} = 2.0 \times 10^{-3} \text{ A/V}$$



$$\overline{i_i^2} = \overline{i_{ia}^2} + \frac{\overline{V_{ia}^2}}{R_F^2} + \overline{i_f^2}$$

M_1 and R_F are dominant sources

$$\begin{aligned} \frac{\overline{i_{ia}^2}}{\Delta f} &= \frac{\omega^2 C_{gs}^2}{g_m^2} (4kT \frac{2}{3} g_m + k \frac{I_D}{F}) \\ &\quad \left(k \frac{I_D}{g_m^2 f} = \frac{k_F}{W L C_{ox} f} \right) \\ &= \frac{\omega^2 C_{gs}^2}{g_m^2} 4kT \frac{2}{3} g_m + \omega^2 C_{gs}^2 \frac{k_F}{W L C_{ox} f} \\ &= \frac{4\pi^2 C_{gs}^2}{g_m} 4kT \frac{2}{3} f^2 + 4\pi^2 C_{gs}^2 \frac{k_F}{\frac{2}{3} C_{gs}} f \\ &= \frac{4\pi^2 C_{gs}^2}{g_m} 4kT \frac{2}{3} f^2 + 4\pi^2 C_{gs} \frac{k_F}{3/2} f \\ &= \frac{4 \times (3.14)^2 \times (2.9 \times 10^{-13})^2}{2.0 \times 10^{-3}} \times 1.7 \times 10^{-20} \times \frac{2}{3} f^2 \\ &\quad + 4 \times (3.14)^2 \times 2.9 \times 10^{-13} \times \frac{3 \times 10^{-24}}{3/2} f \\ &= 1.9 \times 10^{-44} f^2 + 2.3 \times 10^{-35} f \text{ A}^2/\text{Hz} \end{aligned}$$

$$\begin{aligned} \int_{10^{-2}}^{10^5} \frac{\overline{i_{ia}^2}}{\Delta f} df &= 1.9 \times 10^{-44} \times \frac{1}{3} f^3 + 2.3 \times 10^{-35} \times \frac{1}{2} f^2 \Big|_{10^{-2}}^{10^5} \\ &= 6.3 \times 10^{-27} + 1.2 \times 10^{-25} = 1.2 \times 10^{-25} \text{ A}^2 \end{aligned}$$

$$\begin{aligned} \frac{\overline{V_{ia}^2}}{R_F^2 \Delta f} &= \frac{1}{R_F^2} 4kT \frac{2}{3} g_m + \frac{1}{R_F^2} \frac{k_F}{W L C_{ox} f} \\ &= \frac{1}{(10^4)^2} \times 1.7 \times 10^{-20} \times \frac{2}{3} \times 2.0 \times 10^{-3} \end{aligned}$$

$$+ \frac{1}{(10^4)^2} \frac{3 \times 10^{-24}}{100 \times 1 \times 10^{-12} \times 4.3 \times 10^{-3}} \frac{1}{f}$$

$$= 2.3 \times 10^{-31} + 7.0 \times 10^{-20} \frac{1}{f} \text{ A}^2/\text{Hz}$$

$$\int_{10^{-2}}^{10^5} \frac{\overline{V_{ia}^2}}{R_F^2 \Delta f} df = 2.3 \times 10^{-31} f + 7.0 \times 10^{-20} \ln f \Big|_{10^{-2}}^{10^5}$$

$$= 2.3 \times 10^{-26} + 1.1 \times 10^{-18} = 1.1 \times 10^{-18} \text{ A}^2$$

$$\frac{\overline{i_f^2}}{\Delta f} = 4kT \frac{1}{R_F} = 1.7 \times 10^{-20} \frac{1}{10^4} = 1.7 \times 10^{-24} \text{ A}^2/\text{Hz}$$

$$\int_{10^{-2}}^{10^5} \frac{\overline{i_f^2}}{\Delta f} df = 1.7 \times 10^{-24} f \Big|_{10^{-2}}^{10^5} = 1.7 \times 10^{-19} \text{ A}^2$$

$$\begin{aligned} \overline{i_{iT}^2} &= 1.2 \times 10^{-25} + 1.1 \times 10^{-18} + 1.7 \times 10^{-19} \\ &= 1.3 \times 10^{-18} \text{ A}^2 \end{aligned}$$

$$i_{iT} = 1.1 \text{ nA}$$

11.23

$$|B(j\omega)| \gg \beta_0 \gg 1, \frac{I_c}{|B(j\omega)|^2} \approx \frac{I_c}{\beta_0^2} \gg \frac{I_c}{\beta_0} = I_B$$

$$\frac{\overline{i_{ia}^2}}{\Delta f} = 2q [I_B + k' \frac{I_B}{F} + \frac{I_c}{|B(j\omega)|^2}]$$

$$\approx 2q [I_B + k' \frac{I_B}{F}]$$

$$= 2q I_B (1 + \frac{f_a}{f})$$

$$\sim 2 \times 1.6 \times 10^{-19} \times \frac{10^{-3}}{200} = 1.6 \times 10^{-24} \text{ A}^2/\text{Hz}$$

$$\frac{\overline{V_{ia}^2}}{R_F^2 \Delta f} = \frac{1}{R_F^2} 4kT (r_{b1} + \frac{1}{2q g_m})$$

$$\sim \frac{1}{(10^4)^2} \times 1.7 \times 10^{-20} \times 10^3 = 1.7 \times 10^{-25} \text{ A}^2/\text{Hz}$$

$$\ll \frac{\overline{i_{ia}^2}}{\Delta f}$$

$$\frac{\overline{i_i^2}}{\Delta f} = \frac{\overline{i_{ia}^2}}{\Delta f} + \frac{\overline{V_{ia}^2}}{R_F^2 \Delta f} + 4kT \frac{1}{R_F}$$

$$\approx 2q I_B (1 + \frac{f_a}{f}) + 4kT \frac{1}{R_F}$$

$$= 3.2 \times 10^{-19} \times \frac{10^{-3}}{200} (1 + \frac{5000}{f}) + 1.7 \times 10^{-20} \frac{1}{10^4}$$

$$= 3.3 \times 10^{-24} + 8.0 \times 10^{-24} \frac{1}{f} \text{ A}^2/\text{Hz}$$

$$\overline{i_{iT}^2} = \int_{10^{-2}}^{10^5} \frac{\overline{i_i^2}}{\Delta f} df = 3.3 \times 10^{-24} f + 8.0 \times 10^{-24} \ln f \Big|_{10^{-2}}^{10^5}$$

$$= 4.6 \times 10^{-19} \text{ A}^2$$

$$i_{iT} = 0.67 \text{ nA}$$

11.24

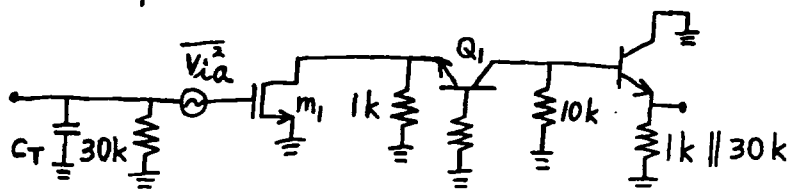
bias from Problem 3.17

$$I_{D1} = 3.79 \text{ mA}$$

$$I_{C1} = 0.26 \text{ mA}$$

$$I_{C2} = I_{D2} = 273 \mu\text{A}$$

forward path



$$C_T = C_S + C_{gs} = 1.5 \text{ pF}$$

ignore Q_1 noise

$$g_{m1} = 9.54 \text{ mA/V}$$

$$\begin{aligned} \frac{\overline{V_{ia}^2}}{\Delta f} &= \frac{1}{g_{m1}^2} (4kT \frac{2}{3} g_{m1} + 4kT \frac{1}{1k}) \\ &= 4kT (\frac{2}{3} \frac{1}{g_{m1}} + \frac{1}{(1k)(g_{m1})^2}) \\ &= 4kT (69.9 + 11) \\ &= 4kT (80.9) \end{aligned}$$

low frequency

$$\frac{\overline{i_i^2}}{\Delta f} = \frac{\overline{V_{ia}^2}}{(30k)^2} + 4kT \frac{1}{30k} \Delta f$$

$$\begin{aligned} \frac{\overline{i_i^2}}{\Delta f} &= 4kT (8.99 \times 10^{-8} + 3.33 \times 10^{-5}) \\ &= 5.56 \times 10^{-25} \frac{\text{A}^2}{\text{Hz}} \end{aligned}$$

$$\text{dominant pole} = \frac{1}{R C_T}$$

$$\begin{aligned} &= \frac{1}{30k (1.5 \text{ pF})} \\ &= 22.2 \text{ Mrad/s} \\ &\quad \downarrow \\ &3.54 \text{ MHz} \end{aligned}$$

11-20

$$\text{loop gain} = T = af$$

$$a = \frac{V_o}{i_s} = \frac{V_o}{V_i} \frac{V_i}{i_s} = \frac{V_o}{V_i} 30k\Omega$$

$$f = \frac{1}{30k\Omega}$$

$$\therefore T = \left| \frac{V_o}{V_i} \right| = 76.5 \quad \text{from Problem 3.17}$$

bandwidth

$$BW/ = (1+T) 3.54 \text{ MHz}$$

$$= 274 \text{ MHz}$$

at 274 MHz

$$\frac{\overline{i_i^2}}{\Delta f} = \frac{\overline{V_{ia}^2}}{|Z_s|^2} + 4kT \frac{1}{30k} \Delta f$$

$$\begin{aligned} |Z_s| &= \frac{1}{\omega C_T} = \frac{1}{2\pi (274 \text{ M})(1.5 \text{ p})} \\ &= 387 \Omega \end{aligned}$$

$$\begin{aligned} \frac{\overline{i_i^2}}{\Delta f} &= 4kT \left(\frac{80.9}{387^2} + \frac{1}{30k} \right) \\ &= 4kT (5.4 \times 10^{-4} + 3.33 \times 10^{-5}) \\ &= 4kT (5.73 \times 10^{-4}) \\ &= 9.54 \times 10^{-24} \frac{\text{A}^2}{\text{Hz}} \end{aligned}$$

11-21

```

BICMOS AMP
VCC 1 0 5V
RL1 1 4 1K
M1 4 2 0 0 NMOS W=300U L=1U
RF 2 7 30K
RE 7 0 1K
RL2 1 3 10K
RBIAS 1 5 10K
Q1 3 5 4 NPN
Q2 5 5 6 NPN
Q3 1 3 7 NPN
M2 6 6 0 0 NMOS W=300U L=1U
CS 2 0 1PF
CGS 2 0 0.5PF
IS 2 0 0A AC 1
.NOISE V(7) IS 10
.AC DEC 10 27.4K 2.74GIG
.PLOT AC VDB(7)
.MODEL NMOS NMOS KP=40U LAMBDA=0 VTO=0.8
.MODEL NPN NPN IS=1E-16 BF=100 RB=0
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.END

```

***** OPERATING POINT INFORMATION TNOM= 25.000 TEMP= 25.000

```

+0:1 = 5.0000 0:2 = 1.5925 0:3 = 2.3733
+0:4 = 1.4810 0:5 = 2.2141 0:6 = 1.4784
+0:7 = 1.5925

```

**** BIPOLAR JUNCTION TRANSISTORS

```

ELEMENT 0:Q1 0:Q2 0:Q3
MODEL 0:NPN 0:NPN 0:NPN
IB 2.4691U 2.7339U 15.7674U
IC 246.9073U 273.3860U 1.5767M
VBE 733.1133M 735.7306M 780.7485M
VCE 892.2554M 735.7306M 3.4075
VBC -159.1421M 0. -2.6267
VBS -2.3733 -2.2141 -5.0000
POWER 222.1145U 203.1498U 5.3850M
BETAD 100.0000 100.0000 100.0000
GM 9.6103M 10.6410M 61.3711M
RPI 10.4055K 9.3976K 1.6294K
RI 0. 0. 0.
RO 1.258E+17 2.569E+14 2.626E+16
CFI 0. 0. 0.
CMU 0. 0. 0.
CCK 0. 0. 0.
CCS 0. 0. 0.
BETAAC 100.0000 100.0000 100.0000
FT 1.529E+12 1.693E+12 9.767E+12

```

**** MOSFETS

```

ELEMENT 0:M1 0:M2
MODEL 0:NMOS 0:NMOS
ID 3.7684M 276.1198U
IBS 0. 0.
IBD -14.8100F -14.7838F
VGS 1.5925 1.4784
VDS 1.4810 1.4784
VBS 0. 0.
VTH 800.0000M 800.0000M
VDSAT 792.5044M 678.3802M
BETA 12.0000M 1.2000M
GAM EFP 527.6252M 527.6252M
GM 9.5101M 814.0563U
GDS 0. 0.
GMB 3.2948M 282.0302U
COTOT 2.046E-16 2.042E-17
CGTOT 69.9239F 7.0031F
CSTOT 69.0632F 6.9063F
CBTOT 6.561E-16 7.634E-17
CGS 69.0632F 6.9063F
CGD 2.046E-16 2.042E-17

```

***** NOISE ANALYSIS TNOM= 25.000 TEMP= 25.000

```

FREQUENCY = 27.4000K HZ
EQUIVALENT INPUT NOISE AT IS = 742.0965F /RT HZ

FREQUENCY = 274.0000K HZ
EQUIVALENT INPUT NOISE AT IS = 742.1044F /RT HZ

FREQUENCY = 2.7400M HZ
EQUIVALENT INPUT NOISE AT IS = 742.8996F /RT HZ

FREQUENCY = 27.4000M HZ
EQUIVALENT INPUT NOISE AT IS = 818.5238F /RT HZ

FREQUENCY = 274.0000M HZ
EQUIVALENT INPUT NOISE AT IS = 3.5324P /RT HZ

```

***** AC ANALYSIS TNOM= 25.000 TEMP= 25.000

FREQ	VDB(7)	60.0000	70.0000	80.0000	90.0000	100.0000
27.4000K	89.428	+	+	+	+	+
34.4946K	89.428	+	+	+	+	+
43.4261K	89.428	+	+	+	+	+
54.6702K	89.428	+	+	+	+	+
68.8257K	89.428	+	+	+	+	+
86.6464K	89.428	+	+	+	+	+
109.0814K	89.428	+	+	+	+	+
137.3253K	89.428	+	+	+	+	+
172.8823K	89.428	+	+	+	+	+
217.6459K	89.428	+	+	+	+	+
274.0000K	89.428	+	+	+	+	+
344.9456K	89.428	+	+	+	+	+
434.2607K	89.428	+	+	+	+	+
546.7019K	89.428	+	+	+	+	+
688.2569K	89.428	+	+	+	+	+
866.4641K	89.428	+	+	+	+	+
1.0908M	89.428	+	+	+	+	+
1.3733M	89.428	+	+	+	+	+
1.7288M	89.428	+	+	+	+	+
2.1765M	89.428	+	+	+	+	+
2.7400M	89.428	+	+	+	+	+
3.4495M	89.427	+	+	+	+	+
4.3426M	89.427	+	+	+	+	+
5.4670M	89.426	+	+	+	+	+
6.8826M	89.425	+	+	+	+	+
8.6646M	89.423	+	+	+	+	+
10.9081M	89.420	+	+	+	+	+
13.7325M	89.416	+	+	+	+	+
17.2882M	89.409	+	+	+	+	+
21.7646M	89.397	+	+	+	+	+
27.4000M	89.380	+	+	+	+	+
34.4946M	89.351	+	+	+	+	+
43.4261M	89.307	+	+	+	+	+
54.6702M	89.238	+	+	+	+	+
68.8257M	89.131	+	+	+	+	+
86.6464M	88.966	+	+	+	+	+
109.0814M	88.716	+	+	+	+	+
137.3253M	88.348	+	+	+	+	+
172.8823M	87.822	+	+	+	+	+
217.6459M	87.100	+	+	+	+	+
274.0000M	86.157	+	+	+	+	+
344.9456M	84.985	+	+	+	+	+
434.2607M	83.604	+	+	+	+	+
546.7019M	82.045	+	+	+	+	+
688.2569M	80.348	+	+	+	+	+
866.4641M	78.550	+	+	+	+	+
1.0908M	76.683	+	+	+	+	+
1.3733M	74.770	+	+	+	+	+
1.7288M	72.825	+	+	+	+	+
2.1765M	70.861	+	+	+	+	+
2.7400M	68.883	+	+	+	+	+

-3DB AT 274 MHZ

```

BICMOS AMP
VCC 1 0 5V
RL1 1 4 1K
M1 4 2 0 0 NMOS W=300U L=1U
RF 2 7 30K
RE 7 0 1K
RL2 1 3 10K
RBIAS 1 5 10K
Q1 3 5 4 NPN
Q2 5 5 6 NPN
Q3 1 3 7 NPN
M2 6 6 0 0 NMOS W=300U L=1U
CS 2 0 1PF
CGS 2 0 0.5PF
IS 2 0 0A AC 1
.NOISE V(7) IS 10
.AC DEC 10 27.4K 2.74GIG
.PLOT AC VDB(7)
.MODEL NMOS NMOS KP=40U LAMBDA=0 VTO=0.8
.MODEL NPN NPN IS=1E-16 BF=100 RB=200
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.END

```

***** OPERATING POINT INFORMATION TNOM= 25.000 TEMP= 25.000

```

+0:1 = 5.0000 0:2 = 1.5925 0:3 = 2.3764
+0:4 = 1.4810 0:5 = 2.2146 0:6 = 1.4783
+0:7 = 1.5925

```

**** BIPOLAR JUNCTION TRANSISTORS

```

ELEMENT 0:Q1 0:Q2 0:Q3
MODEL 0:NPN 0:NPN 0:NPN
IB 2.4660U 2.7334U 15.7670U
IC 246.5960U 273.3409U 1.5767M

```

11-22

```

VBE 733.5741M 736.2730M 783.9014M
VCE 895.3467M 736.2730M 3.4075
VBC -161.7726M 0. -2.6236
VBS -2.3764 -2.2146 -5.0000
POWER 222.5979U 203.2661U 5.3850M
BETAD 100.0000 100.0000 100.0000
GM 9.5982M 10.6392M 61.3697M
API 10.4186K 9.3992K 1.6295K
RX 200.0000 200.0000 200.0000
RO 1.421E+17 2.624E+14 2.626E+16
CPI 0. 0. 0.
CMU 0. 0. 0.
CBI 0. 0. 0.
CCS 0. 0. 0.
BETAAC 100.0000 100.0000 100.0000
FT 1.527E+12 1.693E+12 9.767E+12

```

**** MOSFETS

```

ELEMENT 0:M1 0:M2
MODEL 0:NMOS 0:NMOS
ID 3.7680M 276.0743U
IBS 0. 0.
IBD -14.8102F -14.7832F
VGS 1.5925 1.4783
VDS 1.4810 1.4783
VBS 0. 0.
VTH 800.0000M 800.0000M
VDSAT 792.4686M 678.3243M
BETA 12.0000M 1.2000M
GM KFF 527.6252M 527.6252M
GM 9.5096M 813.9891U
GDS 0. 0.
GMS 3.2946M 282.0070U
COTOT 2.046E-16 2.042E-17
CGTOT 69.9240F 7.0031F
CSTOT 69.0632F 6.9063F
CBTOT 6.562E-16 7.634E-17
CGS 69.0632F 6.9063F
CGD 2.046E-16 2.042E-17

```

***** NOISE ANALYSIS TNO= 25.000 TEMP= 25.000

```

FREQUENCY = 27.4000K HZ
EQUIVALENT INPUT NOISE AT IS = 742.1550F /RT HZ

```

```

FREQUENCY = 274.0000K HZ
EQUIVALENT INPUT NOISE AT IS = 742.1633F /RT HZ

```

```

FREQUENCY = 2.7400M HZ
EQUIVALENT INPUT NOISE AT IS = 742.9961F /RT HZ

```

```

FREQUENCY = 27.4000M HZ
EQUIVALENT INPUT NOISE AT IS = 822.0273F /RT HZ

```

FREQUENCY = 274.0000M HZ

```

**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT 0:RL1 0:RF 0:RE 0:RL2 0:RBIAS
TOTAL 5.468E-16 2.256E-16 9.545E-20 6.958E-17 7.488E-17

```

**** TRANSISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)

```

ELEMENT 0:Q1 0:Q2 0:Q3
RB 1.096E-16 8.551E-17 1.392E-18
RC 0. 0. 0.
RE 0. 0. 0.
IB 1.475E-16 2.506E-19 2.171E-16
IC 4.301E-17 2.054E-17 2.929E-18
FN 0. 0. 0.
TOTAL 3.001E-16 1.063E-16 2.214E-16

```

**** MOSFET SQUARED NOISE VOLTAGES (SQ V/HZ)

```

ELEMENT 0:M1 0:M2
RD 0. 0.
RS 0. 0.
ID 3.4669F 3.501E-16
RX 5.7630K 6.2596K
FN 0. 0.
TOTAL 3.4669F 3.501E-16

```

**** TOTAL OUTPUT NOISE VOLTAGE = 5.3618F SQ V/HZ

= 73.2242M V/RT HZ

TRANSFER FUNCTION VALUE:

V(7)/IS = 20.2744K

EQUIVALENT INPUT NOISE AT IS = 3.6117P /RT HZ

AT HIGH FREQUENCIES, RB=200 OHMS INCREASES THE EQUIVALENT INPUT NOISE CURRENT.

11.25(a) $\frac{1}{f}$ noise dominates

$$\overline{i_{\frac{1}{f}}^2} = gm^2 (\overline{v_{i\frac{1}{f}}^2}) (2)$$

$$= 2 \mu_n C_{ox} \frac{W}{L} I_D \frac{K_f}{WL C_{ox}} \frac{\Delta f}{f} (2)$$

$$= \frac{4 \mu_n K_f I_D}{L^2} \frac{\Delta f}{f}$$

maximize L to minimize $\frac{1}{f}$ noise

$$WL = \frac{10 \mu m^2}{2} = 5 \mu m^2$$

$$W_1 = 0.6 \mu m = W_2$$

$$L_1 = 8.33 \mu m = L_2$$

(b) thermal noise dominates

$$\overline{i_{th}^2} = gm^2 \overline{v_{th}^2} (2) = gm^2 4kT \frac{2}{3} \frac{1}{gm} (2) \Delta f$$

$$= \frac{16 kT gm}{3} \Delta f$$

$$= \frac{16}{3} kT \sqrt{2 I_D \mu_n C_{ox} \frac{W}{L}} \Delta f$$

minimize $\frac{W}{L}$

$$L_1 = L_2 = 8.33 \mu m$$

$$W_1 = W_2 = 0.6 \mu m$$

```

MOS CURRENT SOURCE
VDD 1 0 15V
VOU1 13 0 13V
LBIAS 13 3 1GIGAHENRY
IS 3 0 0A AC 1
IREF 1 2 50UA
M1 2 2 0 0 N W=0.6U L=8.33U
M2 3 2 0 0 N W=0.6U L=8.33U
*****
* CHOOSE ID=IREF=50UA.
* CHOOSE VT=0.7V.
*****
.MODEL N NMOS LEVEL=1 VTO=0.7 KP=3E-24
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.AC DEC 10 100 100MEG
.NOISE V(3) IS 10
.PRINT AC VM(3) ONOISE INOISE
.END

***** OPERATING POINT INFORMATION          TNOM= 25.000 TEMP= 25.000

+0:1      = 15.0000 0:2      = 8.8859 0:3      = 13.0000
+0:13     = 13.0000

**** MOSFETS

ELEMENT 0:M1      0:M2
MODEL   0:N      0:N
ID      50.0000U  50.0000U
IBS     0.        0.
IBD     -88.8585F -130.0000F
VGS     8.8859    8.8859
VDS     8.8859    13.0000
VBS     0.        0.
VTH     700.0000M 700.0000M
VDSAT   8.1859    8.1859
BETA     1.4924U  1.4924U
GAM EFF 527.6252M 527.6252M
GM       12.2162U  12.2162U
GDS      0.        0.
GMS      4.2323U  4.2323U
CDTOT   2.045E-17  2.992E-17
CGTOT   1.1721F  1.1816F
CSTOT   1.1506F  1.1506F
CBTOT   1.082E-18 1.082E-18
CGS     1.1506F  1.1506F
CGD     2.045E-17 2.992E-17

***** NOISE ANALYSIS          TNOM= 25.000 TEMP= 25.000

FREQUENCY = 100.0000 HZ
**** MOSFET SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT 0:M1      0:M2
ID      55.5289M  55.5289M
FN      1.0742K  1.0742K
TOTAL   1.0743K  1.0743K
**** TOTAL OUTPUT NOISE VOLTAGE          = 2.1485K SQ V/HZ
                                           = 46.3521 V/RT HZ

TRANSFER FUNCTION VALUE:
V(3)/IS          = 643.5053G
EQUIVALENT INPUT NOISE AT IS          = 72.0307P /RT HZ

FREQUENCY = 1.0000K HZ
EQUIVALENT INPUT NOISE AT IS          = 22.7834P /RT HZ

FREQUENCY = 10.0000K HZ
EQUIVALENT INPUT NOISE AT IS          = 7.2215P /RT HZ

FREQUENCY = 100.0000K HZ
EQUIVALENT INPUT NOISE AT IS          = 2.3359P /RT HZ

FREQUENCY = 1.0000X HZ
EQUIVALENT INPUT NOISE AT IS          = 887.1333F /RT HZ

FREQUENCY = 10.0000X HZ
EQUIVALENT INPUT NOISE AT IS          = 565.7293P /RT HZ

FREQUENCY = 100.0000X HZ
EQUIVALENT INPUT NOISE AT IS          = 520.9981F /RT HZ
*****
THERMAL NOISE:
AT FREQUENCY = 100 MHZ, FLICKER NOISE BECOMES
NEGLECTIBLY SMALL; WE ONLY SEE THERMAL NOISE AT
THAT FREQUENCY.
TO CHECK THAT THIS IS TRUE, EVALUATE THE THERMAL
NOISE OUTPUT CURRENT:
(16/3)*KT*GM=2.69E-25 SQ A/HZ
(GM FROM MOSFET DATA ABOVE)
--> 5.18E-13 A/RT HZ
THIS MATCHES THE SPICE RESULT ABOVE
COMPARING W/L=0.6UM/8.33UM, 0.8UM/6.25UM, AND 1UM/5UM,
WE SEE THAT THE SMALLEST W/L RATIO GIVES THE LEAST
THERMAL NOISE (AT 100 MHZ).

FLICKER NOISE:
AT LOW FREQUENCIES, FLICKER NOISE DOMINATES.

```

COMPARING W/L=0.6UM/8.33UM, 0.8UM/6.25UM, AND 1UM/5UM,
WE SEE THAT THE SMALLEST W/L RATIO ALSO GIVES THE LEAST
FLICKER NOISE.

```

MOS CURRENT SOURCE
VDD 1 0 15V
VOU1 13 0 13V
LBIAS 13 3 1GIGAHENRY
IS 3 0 0A AC 1
IREF 1 2 50UA
M1 2 2 0 0 N W=0.8U L=6.25U
M2 3 2 0 0 N W=0.8U L=6.25U
*****
* CHOOSE ID=IREF=50UA.
* CHOOSE VT=0.7V.
*****
.MODEL N NMOS LEVEL=1 VTO=0.7 KP=3E-24
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.AC DEC 10 100 100MEG
.NOISE V(3) IS 10
.PRINT AC VM(3) ONOISE INOISE
.END

***** OPERATING POINT INFORMATION          TNOM= 25.000 TEMP= 25.000

+0:1      = 15.0000 0:2      = 6.8406 0:3      = 13.0000
+0:13     = 13.0000

**** MOSFETS

ELEMENT 0:M1      0:M2
MODEL   0:N      0:N
ID      50.0000U  50.0000U
IBS     0.        0.
IBD     -68.4062F -130.0000F
VGS     6.8406    6.8406
VDS     6.8406    13.0000
VBS     0.        0.
VTH     700.0000M 700.0000M
VDSAT   6.1406    6.1406
BETA     2.6520U  2.6520U
GAM EFF 527.6252M 527.6252M
GM       16.2850U  16.2850U
GDS      0.        0.
GMS      5.6419U  5.6419U
CDTOT   1.575E-17 2.993E-17
CGTOT   1.1682F  1.1824F
CSTOT   1.1511F  1.1511F
CBTOT   1.442E-18 1.442E-18
CGS     1.1511F  1.1511F
CGD     1.575E-17 2.993E-17

***** NOISE ANALYSIS          TNOM= 25.000 TEMP= 25.000

FREQUENCY = 100.0000 HZ
**** MOSFET SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT 0:M1      0:M2
ID      74.0251M  74.0251M
FN      1.9082K  1.9082K
TOTAL   1.9083K  1.9083K
**** TOTAL OUTPUT NOISE VOLTAGE          = 3.8166K SQ V/HZ
                                           = 61.7783 V/RT HZ

TRANSFER FUNCTION VALUE:
V(3)/IS          = 643.5115G
EQUIVALENT INPUT NOISE AT IS          = 96.0018P /RT HZ

FREQUENCY = 1.0000K HZ
EQUIVALENT INPUT NOISE AT IS          = 30.3637P /RT HZ

FREQUENCY = 10.0000K HZ
EQUIVALENT INPUT NOISE AT IS          = 9.6186P /RT HZ

FREQUENCY = 100.0000K HZ
EQUIVALENT INPUT NOISE AT IS          = 3.0941P /RT HZ

FREQUENCY = 1.0000X HZ
EQUIVALENT INPUT NOISE AT IS          = 1.1310P /RT HZ

FREQUENCY = 10.0000X HZ
EQUIVALENT INPUT NOISE AT IS          = 670.5658F /RT HZ

FREQUENCY = 100.0000X HZ
EQUIVALENT INPUT NOISE AT IS          = 604.3648F /RT HZ

```

```

MOS CURRENT SOURCE
VDD 1 0 15V
VOU1 13 0 13V
LBIAS 13 3 1GIGAHENRY
IS 3 0 0A AC 1
IREF 1 2 50UA
M1 2 2 0 0 N W=1U L=5U
M2 3 2 0 0 N W=1U L=5U
*****
* CHOOSE ID=IREF=50UA.
* CHOOSE VT=0.7V.
*****

```

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```

.MODEL N NMOS LEVEL=1 VTO=0.7 KP=3E-24
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.AC DEC 10 100 100MEG
.NOISE V(3) IS 10
.PRINT AC VM(3) CNOISE INOISE
.END

```

***** OPERATING POINT INFORMATION TNOISE= 25.000 TEMP= 25.000

```

+0:1      = 15.0000 0:2      = 5.6125 0:3      = 13.0000
+0:13     = 13.0000

```

**** MOSFETS

ELEMENT	0:M1	0:M2
MODEL	0:M	0:M
ID	50.0000U	50.0000U
IBS	0.	0.
IBD	-56.1249F	-130.0000F
VGS	5.6125	5.6125
VDS	5.6125	13.0000
VBS	0.	0.
VTH	700.0000M	700.0000M
VDSAT	4.9125	4.9125
BETA	4.1438U	4.1438U
GAM EFF	527.6252M	527.6252M
GM	20.3563U	20.3563U
GDS	0.	0.
GMB	7.0524U	7.0524U
CDTOT	1.292E-17	2.993E-17
CGTOT	1.1658F	1.1828F
CSTOT	1.1511F	1.1511F
CBTOT	1.801E-18	1.801E-18
CGB	1.1511F	1.1511F
CGD	1.292E-17	2.993E-17

***** NOISE ANALYSIS TNOISE= 25.000 TEMP= 25.000

```

FREQUENCY = 100.0000 HZ
**** MOSFET SQUARED NOISE VOLTAGES (SQ V/Hz)
ELEMENT 0:M1 0:M2
ID 92.5314M 92.5314M
FM 2.9816K 2.9816K
TOTAL 2.9817K 2.9817K
**** TOTAL OUTPUT NOISE VOLTAGE = 5.9633K SQ V/Hz
= 77.2226 V/RT HZ

TRANSFER FUNCTION VALUE:
V(3)/IS = 643.5115G
EQUIVALENT INPUT NOISE AT IS = 120.0018P /RT HZ

FREQUENCY = 1.0000K HZ
EQUIVALENT INPUT NOISE AT IS = 37.9532P /RT HZ

FREQUENCY = 10.0000K HZ
EQUIVALENT INPUT NOISE AT IS = 12.0186P /RT HZ

FREQUENCY = 100.0000K HZ
EQUIVALENT INPUT NOISE AT IS = 3.8532P /RT HZ

FREQUENCY = 1.0000M HZ
EQUIVALENT INPUT NOISE AT IS = 1.3736P /RT HZ

FREQUENCY = 10.0000M HZ
EQUIVALENT INPUT NOISE AT IS = 768.6876F /RT HZ

FREQUENCY = 100.0000M HZ
EQUIVALENT INPUT NOISE AT IS = 678.3094F /RT HZ

```

11.26

$$k_p' = \mu_n C_{ox} = 150 \times 4.3 \times 10^{-7} = 64.7 \mu A/V^2$$

$$k_n' = \mu_n C_{ox} = 450 \times 4.3 \times 10^{-7} = 194 \mu A/V^2$$

$$g_{m1} = \sqrt{2 \times 64.7 \times (150/0.72) \times 100} = 1.64 \text{ mA/V}$$

$$g_{m3} = \sqrt{2 \times 194 \times (50/0.72) \times 100} = 1.64 \text{ mA/V}$$

$$= g_{m1}$$

Noise is dominated by M1-M4

At 100 Hz

M1,2 thermal:

$$\frac{2}{3} \frac{4kT}{g_{m1}} = \frac{2}{3} \frac{1.66 \times 10^{-20}}{1.64 \text{ m}} = 6.75 \times 10^{-18} \text{ V}^2/\text{Hz}$$

M1,2 flicker:

$$\frac{K_f}{WLC_{ox}f} = \frac{3 \times 10^{-24}}{150 \times 0.72 \times 4.3 \times 10^{-15} \times 100}$$

$$= 6.46 \times 10^{-14} \text{ V}^2/\text{Hz}$$

M3,4 thermal:

$$\frac{2}{3} \frac{4kT}{g_{m3}} \frac{g_{m3}^2}{g_{m1}^2} = \frac{2}{3} \frac{1.66 \times 10^{-20}}{1.64 \text{ m}} = 6.75 \times 10^{-18} \text{ V}^2/\text{Hz}$$

M3,4 flicker:

$$\frac{K_f}{WLC_{ox}f} \frac{g_{m3}^2}{g_{m1}^2} = \frac{3 \times 10^{-24}}{50 \times 0.72 \times 4.3 \times 10^{-15} \times 100}$$

$$= 1.94 \times 10^{-13} \text{ V}^2/\text{Hz}$$

$$\overline{U_{ET}^2} = 2[6.75 \times 10^{-18} + 6.46 \times 10^{-14} + 6.75 \times 10^{-18} + 1.94 \times 10^{-13}]$$

$$= 5.17 \times 10^{-13} \text{ V}^2/\text{Hz}$$

$$\sqrt{\overline{U_{ET}^2}} = 719 \text{ nV}/\sqrt{\text{Hz}}$$

Flicker noise is dominant, especially from M3, M4.

At 1 kHz,

M1,2 thermal: $6.75 \times 10^{-18} \text{ V}^2/\text{Hz}$ (same)

M1,2 flicker: $6.46 \times 10^{-15} \text{ V}^2/\text{Hz}$

M3,4 thermal: $6.75 \times 10^{-18} \text{ V}^2/\text{Hz}$ (same)

M3,4 flicker: $1.94 \times 10^{-14} \text{ V}^2/\text{Hz}$

$$\overline{U_{ET}^2} = 5.17 \times 10^{-14} \text{ V}^2/\text{Hz}$$

$$\sqrt{\overline{U_{ET}^2}} = 227 \text{ nV}/\sqrt{\text{Hz}}$$

At 10 kHz,

M1,2 thermal: $6.75 \times 10^{-18} \text{ V}^2/\text{Hz}$ (same)

M1,2 flicker: $6.46 \times 10^{-16} \text{ V}^2/\text{Hz}$

M3,4 thermal: $6.75 \times 10^{-18} \text{ V}^2/\text{Hz}$ (same)

M3,4 flicker: $1.94 \times 10^{-15} \text{ V}^2/\text{Hz}$

$$\overline{U_{ET}^2} = 5.20 \times 10^{-15} \text{ V}^2/\text{Hz}$$

$$\sqrt{\overline{U_{ET}^2}} = 72.1 \text{ nV}/\sqrt{\text{Hz}}$$

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```

OP AMP
VDD 1 0 1.5
VSS 2 0 -1.5
IBIAS 8 2 200U
VIP 11 0 DC -7.315U AC 1
VIN 12 0 0
M1 3 12 5 5 CMOSF L=0.72U W=150U
M2 4 11 5 5 CMOSF L=0.72U W=150U
M3 3 3 2 2 CMOSN L=0.72U W=50U
M4 4 3 2 2 CMOSN L=0.72U W=50U
M5 5 8 1 1 CMOSF L=0.72U W=150U
M6 13 4 2 2 CMOSN L=0.72U W=100U
M7 13 8 1 1 CMOSF L=0.72U W=150U
M8 8 8 1 1 CMOSF L=0.72U W=150U
M9 4 1 14 2 CMOSN L=0.72U W=8.3U
CC 14 13 5P
.MODEL CMOSN NMOS VTO=0.6 KP=194U TOX=80E-10 LAMBDA=0.027778 KF=3.E-24 NLEV=2
.MODEL CMOSF PMOS VTO=-0.8 KP=64.7U TOX=80E-10 LAMBDA=0.055556 KF=3.E-24 NLEV=2
*NMOS: LAMBDA=(LDD/DVDS)/LEFF=0.02U/0.72U=0.027778
*PMOS: LAMBDA=(LDD/DVDS)/LEFF=0.04U/0.72U=0.055556
.OPTIONS NOMOD
.WIDTH OUT=80
.OP
.NOISE V(13) VIP 10
.TF V(13) VIP
.AC DEC 10 100 10K
.NOISE V(13) VIP 10
.PRINT AC VM(13) OMOISE INOISE
.END

```

```

ID 144.0637F 103.9127F 1.048E-16 0.
FN 4.3041N 1.4928N 1.4648P 0.
TOTAL 4.3042N 1.4929N 1.4649P 0.
**** TOTAL OUTPUT NOISE VOLTAGE = 1.0757M SQ V/HZ
= 32.7982M V/RT HZ

TRANSFER FUNCTION VALUE:
V(13)/VIP = 46.9267K
EQUIVALENT INPUT NOISE AT VIP = 698.9248N /RT HZ

FREQUENCY = 1.0000K HZ
EQUIVALENT INPUT NOISE AT VIP = 221.0711M /RT HZ

FREQUENCY = 10.0000K HZ
EQUIVALENT INPUT NOISE AT VIP = 70.0720M /RT HZ

```

***** OPERATING POINT INFORMATION THOM= 25.000 TEMP= 25.000

```

+0:1 = 1.5000 0:2 = -1.5000 0:3 = -780.5838M
+0:4 = -778.9569M 0:5 = 915.2649M 0:8 = 532.1868M
+0:11 = -7.3150U 0:12 = 0. 0:13 = -20.4925U
+0:14 = -778.9569M

```

**** MOSFETS

ELEMENT	0:M1	0:M2	0:M3	0:M4	0:M5	0:M6
MODEL	0:CMOSF	0:CMOSF	0:CMOSN	0:CMOSN	0:CMOSF	0:CMOSN
ID	-97.9782U	-97.9825U	97.9782U	97.9825U	-195.9607U	205.6117U
IBS	0.	0.	0.	0.	0.	0.
IBD	16.9585F	16.9422F	-7.1942F	-7.2104F	5.8474F	-14.9998F
VGS	-915.2649M	-915.2722M	719.4162M	719.4162M	-967.8132M	721.0431M
VDS	-1.6958	-1.6942	719.4162M	721.0431M	-584.7351M	1.5000
VBS	0.	0.	0.	0.	0.	0.
VTH	-800.0000M	-800.0000M	600.0000M	600.0000M	-800.0000M	600.0000M
VDSAT	-115.2649M	-115.2722M	119.4162M	119.4162M	-167.8132M	121.0431M
BETA	14.7491M	14.7479M	13.7415M	13.7421M	13.9170M	28.0671M
GAM EFF	42.2100M	42.2100M	42.2100M	42.2100M	42.2100M	42.2100M
GM	1.7001M	1.7000M	1.6410M	1.6410M	2.3355M	3.3973M
GDS	4.9746U	4.9752U	2.6683U	2.6683U	10.5443U	5.4830U
GMB	47.1187U	47.1178U	45.4807U	45.4827U	64.7298U	94.1606U
CDTOT	1.0541F	1.0531F	1.491E-16	1.494E-16	3.635E-16	6.216E-16
CGTOT	313.6975F	313.6964F	104.3451F	104.3454F	312.4867F	208.9997F
CSTOT	310.7845F	310.7845F	103.5948F	103.5948F	310.7845F	207.1897F
CBTOT	1.8589F	1.8588F	6.012E-16	6.012E-16	1.3388F	1.1885F
CGS	310.7845F	310.7845F	103.5948F	103.5948F	310.7845F	207.1897F
CGD	1.0541F	1.0531F	1.491E-16	1.494E-16	3.635E-16	6.216E-16

ELEMENT	0:M7	0:M8	0:M9
MODEL	0:CMOSF	0:CMOSF	0:CMOSN
ID	-205.6117U	-200.0000U	728.2539F
IBS	0.	0.	-7.2104F
IBD	15.0002F	9.6781F	-7.2104F
VGS	-967.8132M	-967.8132M	2.2790
VDS	-1.5000	-967.8132M	195.8190P
VBS	0.	0.	-721.0431M
VTH	-800.0000M	-800.0000M	616.0014M
VDSAT	-167.8132M	-167.8132M	195.8190P
BETA	14.6025M	14.2039M	2.2364M
GAM EFF	42.2100M	42.2100M	42.2100M
GM	2.4505M	2.3836M	437.9275F
GDS	10.5443U	10.5443U	3.7190M
GMB	67.9177U	66.0640U	8.1034F
CDTOT	9.324E-16	6.016E-16	12.8976F
CGTOT	313.0556F	312.7248F	25.8007F
CSTOT	310.7845F	310.7845F	12.8976F
CBTOT	1.3388F	1.3388F	5.569E-18
CGS	310.7845F	310.7845F	12.8976F
CGD	9.324E-16	6.016E-16	12.8976F

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

```

V(13)/VIP = 47.1075K
INPUT RESISTANCE AT VIP = 9.999E+19
OUTPUT RESISTANCE AT V(13) = 62.3936K

```

***** NOISE ANALYSIS THOM= 25.000 TEMP= 25.000

```

FREQUENCY = 100.0000 HZ
**** MOSFET SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT 0:M1 0:M2 0:M3 0:M4 0:M5
ID 14.2182N 14.2188N 13.6611N 13.7883N 102.2780F
FN 141.7099U 141.7138U 394.2745U 397.9613U 1.4004N
TOTAL 141.7241U 141.7280U 394.2881U 397.9750U 1.4005N
ELEMENT 0:M6 0:M7 0:M8 0:M9

```

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741 OP AMP, INPUT NOISE-VOLTAGE

*** INPUT STAGE

VCC 1 0 15V

VEE 2 0 -15V

Q12 3 3 1 PNP

R5 3 4 39K

Q11 4 4 2 NPN

Q10 6 4 5 NPN

R4 5 2 5K

Q9 6 7 1 PNP

Q8 7 7 1 PNP

Q1 7 8 10 NPN

Q2 7 9 11 NPN

Q3 12 6 10 PNP

Q4 16 6 11 PNP

Q5 12 13 14 NPN

Q6 16 13 15 NPN

R1 14 2 1K

R2 15 2 1K

Q7 1 12 13 NPN

R3 13 2 50K

*** DARLINGTON GAIN STAGE

Q16 1 16 17 NPN

R9 17 2 50K

Q17 19 17 18 NPN

R8 18 2 100

Q13B 19 3 1 PNPB

*** OUTPUT STAGE

Q13A 20 3 1 PNPB

Q19 20 20 21 NPN

Q18 20 21 22 NPN

R10 21 22 40K

Q23 2 19 22 PNP

Q20 2 22 23 PNP 3

R7 23 24 22

R6 25 24 27

Q14 1 20 25 NPN 3

.MODEL NPN NPN BF=250 IS=5E-15 VAF=130

.MODEL PNP PNP BF=50 IS=2E-15 VAF=52

.MODEL PNPB PNPB BF=50 IS=0.5E-15 VAF=52

.MODEL PNPB PNPB BF=50 IS=1.5E-15 VAF=52

V11 8 0 -268.625UV AC 1

V12 9 0 0V

.TF V(24) V11

.NOISE V(24) V11 10

.AC DEC 10 100 10K

.OPTIONS MOPAGE NOMOD

.WIDTH OUT=80

.OPTIONS SPICE

.OP

.PROBE

.END

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

+0:1	= 1.500E+01 0:2	= -1.500E+01 0:3	= 1.431E+01
+0:4	= -1.433E+01 0:5	= -1.490E+01 0:6	= -1.108E+00
+0:7	= 1.441E+01 0:8	= -2.686E-04 0:9	= 0.
+0:10	= -5.444E-01 0:11	= -5.442E-01 0:12	= -1.389E+01
+0:13	= -1.444E+01 0:14	= -1.499E+01 0:15	= -1.499E+01
+0:16	= -1.370E+01 0:17	= -1.427E+01 0:18	= -1.493E+01
+0:19	= -1.257E+00 0:20	= 5.932E-01 0:21	= 2.625E-02
+0:22	= -6.058E-01 0:23	= 6.808E-04 0:24	= 3.295E-03
+0:25	= 6.503E-03		

**** BIPOLAR JUNCTION TRANSISTORS

ELEMENT	0:Q12	0:Q11	0:Q10	0:Q9	0:Q8	0:Q1
MODEL	0:PNP	0:NPN	0:NPN	0:PNP	0:PNP	0:NPN
IB	-1.413E-05	2.926E-06	6.988E-08	-2.928E-07	-2.928E-07	2.736E-08
IC	-7.063E-04	7.316E-04	1.925E-05	-1.901E-05	-1.464E-05	7.597E-06
VBE	-6.877E-01	6.649E-01	5.683E-01	-5.875E-01	-5.875E-01	5.441E-01
VCE	-6.877E-01	6.649E-01	1.379E+01	-1.610E+01	-5.875E-01	1.495E+01
VBC	0.	0.	-1.322E+01	1.552E+01	0.	-1.441E+01
VS	-1.431E+01	1.433E+01	1.108E+00	-1.441E+01	-1.441E+01	-1.441E+01
POWER	4.955E-04	4.884E-04	2.656E-04	3.064E-04	8.771E-06	1.136E-04
BETAD	5.000E+01	2.500E+02	2.754E+02	6.492E+01	5.000E+01	2.777E+02
GM	2.729E-02	2.828E-02	7.441E-04	7.346E-04	5.657E-04	2.937E-04
RPI	1.831E+03	8.838E+03	3.701E+05	8.834E+04	8.834E+04	9.454E+05
RX	0.	0.	0.	0.	0.	0.
RO	7.362E+04	1.777E+05	7.440E+06	3.552E+06	3.552E+06	1.900E+07
CPI	0.	0.	0.	0.	0.	0.
CMU	0.	0.	0.	0.	0.	0.
CBX	0.	0.	0.	0.	0.	0.
CCS	0.	0.	0.	0.	0.	0.
BETAAC	4.997E+01	2.499E+02	2.753E+02	6.490E+01	4.997E+01	2.776E+02
FT	4.344E+12	4.500E+12	1.184E+11	1.169E+11	9.002E+10	4.674E+10

ELEMENT	0:Q2	0:Q3	0:Q4	0:Q5	0:Q6	0:Q7
MODEL	0:NPN	0:PNP	0:PNP	0:NPN	0:NPN	0:NPN
IB	2.746E-08	-1.205E-07	-1.213E-07	2.975E-08	2.974E-08	3.632E-08
IC	7.626E-06	-7.504E-06	-7.532E-06	7.468E-06	7.476E-06	1.110E-05
VBE	5.442E-01	-5.645E-01	-5.647E-01	5.463E-01	5.462E-01	5.514E-01
VCE	1.495E+01	-1.335E+01	-1.316E+01	1.097E+00	1.285E+00	2.944E+01
VBC	-1.441E+01	1.278E+01	1.259E+01	-5.514E-01	-7.393E-01	-2.889E+01
VS	-1.441E+01	1.108E+00	1.108E+00	1.389E+01	1.370E+01	-1.500E+01
POWER	1.141E-04	1.003E-04	9.921E-05	8.214E-06	9.627E-06	3.268E-04
BETAD	2.777E+02	6.229E+01	6.211E+01	2.510E+02	2.514E+02	3.055E+02

GM	2.948E-04	2.900E-04	2.911E-04	2.887E-04	2.890E-04	4.290E-04
RPI	9.419E+05	2.147E+05	2.132E+05	8.695E+05	8.698E+05	7.121E+05
RX	0.	0.	0.	0.	0.	0.
RO	1.893E+07	8.633E+06	8.576E+06	1.748E+07	1.748E+07	1.431E+07
CPI	0.	0.	0.	0.	0.	0.
CMU	0.	0.	0.	0.	0.	0.
CBX	0.	0.	0.	0.	0.	0.
CCS	0.	0.	0.	0.	0.	0.
BETAAC	2.776E+02	6.226E+01	6.208E+01	2.510E+02	2.513E+02	3.055E+02
FT	4.691E+10	4.615E+10	4.633E+10	4.594E+10	4.599E+10	6.828E+10

ELEMENT	0:Q16	0:Q17	0:Q13B	0:Q13A	0:Q19	0:Q18
MODEL	0:NPN	0:NPN	0:PNPB	0:PNPB	0:NPN	0:NPN
IB	5.593E-08	2.516E-06	-1.059E-05	-3.531E-06	6.623E-08	8.209E-07
IC	1.707E-05	6.918E-04	-6.883E-04	-2.232E-04	1.656E-05	2.061E-04
VBE	5.626E-01	6.610E-01	-6.877E-01	-6.877E-01	5.670E-01	6.321E-01
VCE	2.927E+01	1.367E+01	-1.625E+01	-1.440E+01	5.670E-01	1.199E+00
VBC	-2.870E+01	-1.301E+01	1.557E+01	1.371E+01	0.	-5.670E-01
VS	-1.500E+01	1.257E+00	-1.431E+01	-1.431E+01	-5.932E-01	-5.932E-01
POWER	4.996E-04	9.461E-03	1.120E-02	3.217E-03	9.424E-06	2.476E-04
BETAD	3.052E+02	2.750E+02	6.497E+01	6.319E+01	2.500E+02	2.510E+02
GM	6.598E-04	2.674E-02	2.660E-02	8.625E-03	6.400E-04	7.967E-03
RPI	4.624E+05	1.028E+04	2.441E+03	7.323E+03	3.905E+05	3.150E+04
RX	0.	0.	0.	0.	0.	0.
RO	9.298E+06	2.067E+05	9.816E+04	2.944E+05	7.852E+06	6.334E+05
CPI	0.	0.	0.	0.	0.	0.
CMU	0.	0.	0.	0.	0.	0.
CBX	0.	0.	0.	0.	0.	0.
CCS	0.	0.	0.	0.	0.	0.
BETAAC	3.051E+02	2.749E+02	6.494E+01	6.316E+01	2.499E+02	2.510E+02
FT	1.050E+11	4.256E+12	4.234E+12	1.372E+12	1.018E+11	1.268E+12

ELEMENT	0:Q23	0:Q20	0:Q14
MODEL	0:PNP	0:PNP	0:NPN
IB	-3.497E-06	-1.833E-06	4.263E-07
IC	-2.211E-04	-1.170E-04	1.184E-04
VBE	-6.516E-01	-6.065E-01	5.867E-01
VCE	-1.439E+01	-1.500E+01	1.499E+01
VBC	1.374E+01	1.439E+01	-1.440E+01
VS	1.257E+00	6.058E-01	-1.500E+01
POWER	3.184E-03	1.756E-03	1.775E-03
BETAD	6.321E+01	6.384E+01	2.777E+02
GM	8.544E-03	4.521E-03	4.577E-03
RPI	7.395E+03	1.411E+04	6.066E+04
RX	0.	0.	0.
RO	2.973E+05	5.675E+05	1.219E+06
CPI	0.	0.	0.
CMU	0.	0.	0.
CBX	0.	0.	0.
CCS	0.	0.	0.
BETAAC	6.318E+01	6.381E+01	2.776E+02
FT	1.359E+12	7.196E+11	7.284E+11

**** SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(24)/V11	= 3.126E+05
INPUT RESISTANCE AT V11	= 4.759E+06
OUTPUT RESISTANCE AT V(24)	= 1.339E+02

***** NOISE ANALYSIS THOM= 27.000 TEMP= 27.000

FREQUENCY = 1.000E+02 HZ

**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)

ELEMENT	0:R5	0:R4	0:R1	0:R2	0:R3
TOTAL	1.346E-15	1.927E-11	3.845E-06	3.851E-06	1.883E-11
ELEMENT	0:R9	0:R8	0:R10	0:R7	0:R6
TOTAL	1.797E-11	2.280E-13	2.276E-19	8.168E-20	1.242E-19

**** TRANSISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)

ELEMENT	0:Q12	0:Q11	0:Q10	0:Q9	0:Q8
IB	2.433E-14	2.719E-16	1.320E-13	1.375E-12	1.375E-12
IC	1.216E-12	6.797E-14	2.660E-12	5.732E-11	6.876E-11
TOTAL	1.241E-12	6.825E-14	2.792E-12	5.870E-11	7.014E-11
ELEMENT	0:Q1	0:Q2	0:Q3	0:Q4	0:Q5
IB	9.791E-09	9.896E-09	4.287E-08	4.396E-08	2.142E-09
IC	2.739E-06	2.729E-06	2.881E-06	2.872E-06	6.673E-06
TOTAL	2.749E-06	2.738E-06	2.924E-06	2.916E-06	6.675E-06
ELEMENT	0:Q6	0:Q7	0:Q16	0:Q17	0:Q13B
IB	2.283E-09	5.350E-08	8.238E-08	4.415E-11	1.825E-14
IC	6.676E-06	2.020E-10	2.966E-10	3.686E-13	1.337E-12
TOTAL	6.679E-06	5.370E-08	8.267E-08	4.451E-11	1.356E-12
ELEMENT	0:Q13A	0:Q19	0:Q18	0:Q23	0:Q20
IB	6.082E-15	1.399E-20	1.445E-19	6.565E-15	8.508E-19
IC	1.398E-16	3.497E-18	3.308E-19	1.248E-16	5.716E-19
TOTAL	6.222E-15	3.511E-18	4.752E-19	6.690E-15	1.422E-18
ELEMENT	0:Q14				
IB	2.232E-19				
IC	5.433E-19				
TOTAL	7.666E-19				

**** TOTAL OUTPUT NOISE VOLTAGE

= 3.251E-05 SQ V/HZ

= 5.702E-03 V/RT HZ

TRANSFER FUNCTION VALUE:	
V(24)/V11	= 3.126E+05
EQUIVALENT INPUT NOISE AT V11	= 1.824E-08 /RT HZ

FREQUENCY = 1.000E+03 HZ	
EQUIVALENT INPUT NOISE AT V11	= 1.824E-08 /RT HZ

BY SPICE:
EQUIVALENT INPUT NOISE VOLTAGE = 3.33E-16 SQ V/HZ
BY HAND CALCULATION:
EQUIVALENT INPUT NOISE VOLTAGE = 2.66E-16 SQ V/HZ

741 OP AMP, INPUT NOISE-CURRENT

```
*** INPUT STAGE
VCC 1 0 15V
VEE 2 0 -15V
Q12 3 3 1 PNP
R5 3 4 39K
Q11 4 4 2 NPN
Q10 6 4 5 NPN
R4 5 2 5K
Q9 6 7 1 PNP
Q8 7 7 1 PNP
Q1 7 8 10 NPN
LBIA5 8 8 1GIGAHENRY
IS 8 8 0A AC 1
Q2 7 9 11 NPN
Q3 12 6 10 PNP
Q4 16 6 11 PNP
Q5 12 13 14 NPN
Q6 16 13 15 NPN
R1 14 2 1K
R2 15 2 1K
Q7 1 12 13 NPN
R3 13 2 50K
*** DARLINGTON GAIN STAGE
Q16 1 16 17 NPN
R9 17 2 50K
Q17 19 17 18 NPN
R8 18 2 100
Q13B 19 3 1 PNPB
*** OUTPUT STAGE
Q13A 20 3 1 PMPA
Q19 20 20 21 NPN
Q18 20 21 22 NPN
R10 21 22 40K
Q23 2 19 22 PNP
Q20 2 22 23 PNP 3
R7 23 24 22
R6 25 24 27
Q14 1 20 25 NPN 3
.MODEL NPN NPN BF=250 IS=5E-15 VAF=130
.MODEL PNP PNP BF=50 IS=2E-15 VAF=52
.MODEL PMPA PMP BF=50 IS=0.5E-15 VAF=52
.MODEL PNPB PNP BF=50 IS=1.5E-15 VAF=52
V11 8 0 -268.6250V
V12 9 0 0V
.TF V(24) V11
.NOISE V(24) IS 10
.AC DEC 10 100 10K
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.PROBE
.END
```

```
***** NOISE ANALYSIS
TNOM= 27.000 TEMP= 27.000
FREQUENCY = 1.000E+02 HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT 0:R5 0:R4 0:R1 0:R2 0:R3
TOTAL 5.745E-11 9.182E-06 6.131E-06 6.137E-06 2.773E-11
ELEMENT 0:R9 0:R8 0:R10 0:R7 0:R6
TOTAL 2.725E-11 1.617E-13 2.271E-19 8.192E-20 1.238E-19
**** TRANSISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT 0:Q12 0:Q11 0:Q10 0:Q9 0:Q8
IB 3.051E-14 1.285E-10 6.290E-08 6.550E-07 6.550E-07
IC 1.525E-12 3.214E-08 1.268E-06 2.731E-05 3.275E-05
TOTAL 1.556E-12 3.226E-08 1.330E-06 2.797E-05 3.341E-05
ELEMENT 0:Q1 0:Q2 0:Q3 0:Q4 0:Q5
IB 1.934E-02 6.115E-08 1.338E-08 8.781E-07 3.420E-09
IC 6.965E-05 9.643E-11 2.612E-10 1.536E-08 1.064E-05
TOTAL 1.941E-02 6.124E-08 1.364E-08 8.935E-07 1.064E-05
ELEMENT 0:Q6 0:Q7 0:Q16 0:Q17 0:Q13B
IB 3.635E-09 8.533E-08 1.313E-07 6.673E-11 2.288E-14
IC 1.064E-05 2.975E-10 4.497E-10 4.441E-13 1.274E-12
TOTAL 1.064E-05 8.562E-08 1.318E-07 6.717E-11 1.297E-12
ELEMENT 0:Q13A 0:Q19 0:Q18 0:Q23 0:Q20
IB 7.627E-15 1.396E-20 1.441E-19 6.252E-15 8.105E-19
IC 1.340E-16 3.489E-18 3.300E-19 1.194E-16 5.689E-19
TOTAL 7.761E-15 3.503E-18 6.741E-19 6.372E-15 1.379E-18
ELEMENT 0:Q14
IB 2.132E-19
IC 5.410E-19
TOTAL 7.542E-19
**** TOTAL OUTPUT NOISE VOLTAGE = 1.951E-02 SQ V/HZ
= 1.397E-01 V/RT HZ
TRANSFER FUNCTION VALUE:
V(24)/IS = 1.487E+12
EQUIVALENT INPUT NOISE AT IS = 9.388E-14 /RT HZ
FREQUENCY = 1.000E+03 HZ
EQUIVALENT INPUT NOISE AT IS = 9.388E-14 /RT HZ
FREQUENCY = 9.999E+03 HZ
```

EQUIVALENT INPUT NOISE AT IS = 9.388E-14 /RT HZ

EQUIVALENT INPUT NOISE CURRENT = 8.81E-27 SQ A/HZ

741 OP AMP, INPUT NOISE-VOLTAGE

```
* FLICKER NOISE
* 2*Q*IB = KF*IB/F AT CORNER FREQ = 1KHZ
* KF=3.2E-16
*** INPUT STAGE
VCC 1 0 15V
VEE 2 0 -15V
Q12 3 3 1 PNP
R5 3 4 39K
Q11 4 4 2 NPN
Q10 6 4 5 NPN
R4 5 2 5K
Q9 6 7 1 PNP
Q8 7 7 1 PNP
Q1 7 8 10 NPN
Q2 7 9 11 NPN
Q3 12 6 10 PNP
Q4 16 6 11 PNP
Q5 12 13 14 NPN
Q6 16 13 15 NPN
R1 14 2 1K
R2 15 2 1K
Q7 1 12 13 NPN
R3 13 2 50K
*** DARLINGTON GAIN STAGE
Q16 1 16 17 NPN
R9 17 2 50K
Q17 19 17 18 NPN
R8 18 2 100
Q13B 19 3 1 PNPB
*** OUTPUT STAGE
Q13A 20 3 1 PMPA
Q19 20 20 21 NPN
Q18 20 21 22 NPN
R10 21 22 40K
Q23 2 19 22 PNP
Q20 2 22 23 PNP 3
R7 23 24 22
R6 25 24 27
Q14 1 20 25 NPN 3
* ADD FLICKER NOISE
.MODEL NPN NPN BF=250 IS=5E-15 VAF=130 KF=3.2E-16 AF=1
.MODEL PNP PNP BF=50 IS=2E-15 VAF=52 KF=3.2E-16 AF=1
.MODEL PMPA PMP BF=50 IS=0.5E-15 VAF=52 KF=3.2E-16 AF=1
.MODEL PNPB PNP BF=50 IS=1.5E-15 VAF=52 KF=3.2E-16 AF=1
V11 8 0 -268.6250V AC 1
V12 9 0 0V
.TF V(24) V11
.NOISE V(24) V11 10
.AC DEC 10 1 10K
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.PROBE
```

```
***** NOISE ANALYSIS
TNOM= 27.000 TEMP= 27.000
FREQUENCY = 1.000E+00 HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT 0:R5 0:R4 0:R1 0:R2 0:R3
TOTAL 1.346E-15 1.927E-11 3.845E-06 3.851E-06 1.883E-11
ELEMENT 0:R9 0:R8 0:R10 0:R7 0:R6
TOTAL 1.797E-11 2.280E-13 2.276E-19 8.168E-20 1.242E-19
**** TRANSISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)
ELEMENT 0:Q12 0:Q11 0:Q10 0:Q9 0:Q8
IB 2.433E-14 2.719E-16 1.320E-13 1.375E-12 1.375E-12
IC 1.216E-12 6.797E-14 2.660E-12 5.732E-11 6.876E-11
FW 2.430E-11 2.715E-13 1.318E-10 1.373E-09 1.373E-09
TOTAL 2.554E-11 3.398E-13 1.346E-10 1.432E-09 1.444E-09
ELEMENT 0:Q1 0:Q2 0:Q3 0:Q4 0:Q5
IB 9.791E-09 9.896E-09 4.287E-08 4.396E-08 2.142E-09
IC 2.739E-06 2.729E-06 2.881E-06 2.872E-06 6.673E-06
FW 9.778E-06 9.883E-06 4.281E-05 4.390E-05 2.139E-06
TOTAL 1.253E-05 1.262E-05 4.573E-05 4.681E-05 8.814E-06
ELEMENT 0:Q6 0:Q7 0:Q16 0:Q17 0:Q13B
IB 2.283E-09 5.350E-08 8.238E-08 4.415E-11 1.825E-14
IC 6.676E-06 2.020E-10 2.966E-10 3.686E-13 1.337E-12
FW 2.280E-06 5.342E-05 8.227E-05 4.409E-08 1.822E-11
TOTAL 8.959E-06 5.348E-05 8.235E-05 4.413E-08 1.958E-11
ELEMENT 0:Q13A 0:Q19 0:Q18 0:Q23 0:Q20
IB 6.082E-15 1.399E-20 1.445E-19 6.565E-15 8.508E-19
IC 1.398E-16 3.497E-18 3.308E-19 1.248E-16 5.716E-19
FW 6.074E-12 1.397E-17 1.443E-16 6.556E-12 8.497E-16
TOTAL 6.080E-12 1.748E-17 1.448E-16 6.563E-12 8.511E-16
ELEMENT 0:Q14
IB 2.232E-19
IC 5.433E-19
FW 2.229E-16
TOTAL 2.237E-16
**** TOTAL OUTPUT NOISE VOLTAGE = 2.790E-04 SQ V/HZ
= 1.670E-02 V/RT HZ
TRANSFER FUNCTION VALUE:
V(24)/V11 = 3.126E+05
```


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EQUIVALENT INPUT NOISE AT V11 = 5.343E-08 /RT HZ

FREQUENCY = 9.999E+00 HZ
EQUIVALENT INPUT NOISE AT V11 = 2.418E-08 /RT HZ

FREQUENCY = 1.000E+02 HZ
EQUIVALENT INPUT NOISE AT V11 = 1.892E-08 /RT HZ

FREQUENCY = 1.000E+03 HZ
EQUIVALENT INPUT NOISE AT V11 = 1.831E-08 /RT HZ

FREQUENCY = 9.999E+03 HZ
EQUIVALENT INPUT NOISE AT V11 = 1.825E-08 /RT HZ

741 OP AMP, INPUT NOISE-CURRENT

* FLICKER NOISE
* 2*Q*IB = KF*IB/F AT CORNER FREQ = 1KHZ
* KF=3.2E-16

*** INPUT STAGE
VCC 1 0 15V
VEE 2 0 -15V
Q12 3 3 1 PNP
R5 3 4 39K
Q11 4 4 2 NPN
Q10 6 4 5 NPN
R4 5 2 5K
Q9 6 7 1 PNP
Q8 7 7 1 PNP
Q1 7 8 10 NPN
LEIAS 8 8 1GIGAHENRY
IS 8 8 0 0A AC 1
Q2 7 9 11 NPN
Q3 12 6 10 PNP
Q4 16 6 11 PNP
Q5 12 13 14 NPN
Q6 16 13 15 NPN
R1 14 2 1K
R2 15 2 1K
Q7 1 12 13 NPN
R3 13 2 50K

*** DARLINGTON GAIN STAGE

Q16 1 16 17 NPN
R9 17 2 50K
Q17 19 17 18 NPN
R8 18 2 100
Q13B 19 3 1 PNPB
*** OUTPUT STAGE
Q13A 20 3 1 PNPA
Q19 20 20 21 NPN
Q18 20 21 22 NPN
R10 21 22 40K
Q23 2 19 22 PNP
Q20 2 22 23 PNP 3
R7 23 24 22
R6 25 24 27
Q14 1 20 25 NPN 3

* ADD FLICKER NOISE
.MODEL NPN NPN BF=250 IS=5E-15 VAF=130 KF=3.2E-16 AF=1
.MODEL PNP PNP BF=50 IS=2E-15 VAF=52 KF=3.2E-16 AF=1
.MODEL PNPA PNP BF=50 IS=0.5E-15 VAF=52 KF=3.2E-16 AF=1
.MODEL PNPB PNP BF=50 IS=1.5E-15 VAF=52 KF=3.2E-16 AF=1
V11 8 0 -268.625UV
V12 9 0 0V
.TF V(24) V11
.NOISE V(24) IS 10
.AC DEC 10 1 10K
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS SPICE
.OP
.PROBE
.END

***** NOISE ANALYSIS THOM= 27.000 TEMP= 27.000

FREQUENCY = 1.000E+00 HZ
**** RESISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)

ELEMENT	0:R5	0:R4	0:R1	0:R2	0:R3
TOTAL	5.745E-11	9.182E-06	6.131E-06	6.137E-06	2.773E-11

ELEMENT 0:R9 0:R8 0:R10 0:R7 0:R6

TOTAL	2.725E-11	1.617E-13	2.271E-19	8.192E-20	1.238E-19
-------	-----------	-----------	-----------	-----------	-----------

**** TRANSISTOR SQUARED NOISE VOLTAGES (SQ V/HZ)

ELEMENT	0:Q12	0:Q11	0:Q10	0:Q9	0:Q8
IB	3.051E-14	1.285E-10	6.290E-08	6.550E-07	6.550E-07
IC	1.525E-12	3.214E-08	1.268E-06	2.731E-05	3.275E-05
FN	3.047E-11	1.284E-07	6.281E-05	6.541E-04	6.541E-04
TOTAL	3.202E-11	1.606E-07	6.414E-05	6.821E-04	6.875E-04

ELEMENT	0:Q1	0:Q2	0:Q3	0:Q4	0:Q5
IB	1.934E-02	6.115E-08	1.338E-08	8.781E-07	3.420E-09
IC	6.965E-05	9.799E-11	2.628E-10	1.536E-08	1.064E-05
FN	1.930E+01	6.106E-05	1.337E-05	8.769E-04	3.415E-06
TOTAL	1.932E+01	6.112E-05	1.338E-05	8.778E-04	1.406E-05

ELEMENT	0:Q6	0:Q7	0:Q16	0:Q17	0:Q13B
IB	3.635E-09	8.533E-08	1.313E-07	6.673E-11	2.288E-14
IC	1.064E-05	2.975E-10	4.497E-10	4.441E-13	1.274E-12
FN	3.630E-06	8.521E-05	1.311E-04	6.663E-08	2.285E-11
TOTAL	1.427E-05	8.530E-05	1.313E-04	6.670E-08	2.415E-11

ELEMENT 0:Q13A 0:Q19 0:Q18 0:Q23 0:Q20

	IB 7.627E-15	1.396E-20	1.441E-19	6.252E-15	8.105E-19
IC	1.340E-16	3.489E-18	3.300E-19	1.194E-16	5.689E-19
FN	7.617E-12	1.394E-17	1.439E-16	6.244E-12	8.094E-16
TOTAL	7.624E-12	1.744E-17	1.444E-16	6.250E-12	8.108E-16

ELEMENT 0:Q14

	IB 2.132E-19	IC 5.410E-19	FN 2.129E-16	TOTAL 2.137E-16
--	--------------	--------------	--------------	-----------------

**** TOTAL OUTPUT NOISE VOLTAGE = 1.933E+01 SQ V/HZ
= 4.396E+00 V/RT HZ

TRANSFER FUNCTION VALUE:
V(24)/IS = 1.487E+12
EQUIVALENT INPUT NOISE AT IS = 2.955E-12 /RT HZ

FREQUENCY = 9.999E+00 HZ
EQUIVALENT INPUT NOISE AT IS = 9.387E-13 /RT HZ

FREQUENCY = 1.000E+02 HZ
EQUIVALENT INPUT NOISE AT IS = 3.099E-13 /RT HZ

FREQUENCY = 1.000E+03 HZ
EQUIVALENT INPUT NOISE AT IS = 1.324E-13 /RT HZ

FREQUENCY = 9.999E+03 HZ
EQUIVALENT INPUT NOISE AT IS = 9.842E-14 /RT HZ

11-30

11.28

$$(a) C_{ox} = \frac{\epsilon}{t_{ox}} = \frac{3.9 \times 8.85 \times 10^{-12}}{80 \times 10^{-10}} = 4.3 \times 10^{-3} \text{ F/m}^2$$

$$C_{gs} = \frac{2}{3} W L C_{ox}$$

$$= \frac{2}{3} \times 50 \times 10^{-6} \times 0.5 \times 10^{-6} \times 4.3 \times 10^{-3}$$

$$= 7.2 \times 10^{-14} \text{ F} = 72 \text{ fF}$$

$$2q I_G \Delta f = \frac{16}{15} k T 4 \pi^2 f^2 C_{gs}^2 \Delta f$$

$$f^2 = \frac{15}{32 \pi^2} \frac{1}{V_T} I_G \frac{1}{C_{gs}^2}$$

$$= \frac{15}{32 \pi^2} \frac{1}{26 \times 10^{-3}} 0.05 \times 10^{-5} \frac{1}{(7.2 \times 10^{-14})^2}$$

$$= 1.8 \times 10^{10} \text{ Hz}^2$$

$$f = 1.3 \times 10^5 \text{ Hz} = 130 \text{ kHz}$$

$$(b) \int_0^{f_{BW}} 2q I_G df = 2q I_G f_{BW}$$

$$\int_0^{f_{BW}} \frac{16}{15} k T 4 \pi^2 f^2 C_{gs}^2 df$$

$$= \frac{16}{15} k T 4 \pi^2 C_{gs}^2 \frac{1}{3} f_{BW}^3$$

$$2q I_G f_{BW} = \frac{16}{15} k T 4 \pi^2 C_{gs}^2 \frac{1}{3} f_{BW}^3$$

$$f_{BW}^2 = \frac{45}{32 \pi^2} \frac{1}{V_T} I_G \frac{1}{C_{gs}^2}$$

$$= \frac{45}{32 \pi^2} \frac{1}{26 \times 10^{-3}} 0.05 \times 10^{-5} \frac{1}{(7.2 \times 10^{-14})^2}$$

$$= 5.3 \times 10^{10} \text{ Hz}^2$$

$$f_{BW} = 2.3 \times 10^5 \text{ Hz} = 230 \text{ kHz}$$

Chapter 12

12.1

$$V_{ic} - V_{tn1} < V_{o1} < V_{DD} - |V_{ov3}|$$

$$0 - 0.6 < V_{o1} < 2.5 - 0.2$$

$$-0.6V < V_{o1} < 2.3V$$

It is the same for V_{o2} .

$$\text{If } V_{oc} = \frac{2.3 - 0.6}{2} = 0.85V,$$

the largest symmetric differential output swing can be achieved.

$$V_{oip} = \frac{2.3 + 0.6}{2} = 1.45V$$

$$V_{odp} = 2V_{oip} = 2.9V$$

12.2

$$-V_{SS} + V_{ov6} < V_{o1} < V_{DD} - |V_{ov7}|$$

$$-2.5 + 0.2 < V_{o1} < 2.5 - 0.2$$

$$-2.3V < V_{o1} < 2.3V$$

It is the same for V_{o2} .

$$\text{If } V_{oc} = \frac{2.3 - 2.3}{2} = 0V, \text{ the}$$

largest symmetric differential output swing can be achieved.

$$V_{oip} = \frac{2.3 + 2.3}{2} = 2.3V$$

$$V_{odp} = 2V_{oip} = 4.6V$$

12.3

12-2

FULLY DIFFERENTIAL OP AMP

```

VDD 1 0 1.65
VSS 2 0 -1.65
VI 3 4 DC 0 SIN (0 1E-4 1K)
VB1 14 0 0.38
VB2 15 0 -0.56
VB3 16 0 -0.67
VCM 13 0 0
M1 7 3 5 1 CMOSF W=77U L=1U
M2 8 4 5 1 CMOSF W=77U L=1U
M3 7 15 2 2 CMOSN W=4U L=1U
M4 8 15 2 2 CMOSN W=4U L=1U
M5 5 6 1 1 CMOSF W=25U L=1U
M6 9 8 2 2 CMOSN W=16U L=1U
M7 9 14 1 1 CMOSF W=50U L=1U
M8 10 7 2 2 CMOSN W=16U L=1U
M10 10 14 1 1 CMOSF W=50U L=1U
M21 6 9 11 2 CMOSN W=8.4U L=1U
M22 1 13 11 2 CMOSN W=8.4U L=1U
M23 1 13 12 2 CMOSN W=8.4U L=1U
M24 6 10 12 2 CMOSN W=8.4U L=1U
M25 6 6 1 1 CMOSF W=25U L=1U
M26 11 16 2 2 CMOSN W=14U L=1U
M27 12 16 2 2 CMOSN W=14U L=1U
R1 3 0 1G
R2 4 0 1G
C1 7 10 1.39P
C2 8 9 1.39P
.MODEL CMOSN NMOS VTO=0.6 KP=194U TOX=8E-9 LAMBDA=0.027778 KF=3.E-24 NLEV=2
.MODEL CMOSF PMOS VTO=-0.8 KP=64.7U TOX=8E-9 LAMBDA=0.055556 KF=3.E-24 NLEV=2
.OPTIONS NOMOD
.TRAN 1U 10M
.FOUR 1K V(9, 10)
.DC VI -1M, 1M, 0.1M
.PLOT DC V(9, 10)
.WIDTH OUT=80
.OPTIONS SPICE
.END

```

***** DC TRANSFER CURVES THOM= 27.000 TEMP= 27.000

VOLT (A)	V(9,10)								
	-2.000E+00	-1.000E+00	0.	1.000E+00	2.000E+00				
-1.000E-03	1.80E+00								
-9.000E-04	1.78E+00								
-8.000E-04	1.77E+00								
-7.000E-04	1.76E+00								
-6.000E-04	1.74E+00								
-5.000E-04	1.72E+00								
-4.000E-04	1.69E+00								
-3.000E-04	1.65E+00								
-2.000E-04	1.42E+00								
-1.000E-04	7.16E-01								
0.	0.								
1.000E-04	-7.16E-01								
2.000E-04	-1.42E+00								
3.000E-04	-1.65E+00								
4.000E-04	-1.69E+00								
5.000E-04	-1.72E+00								
6.000E-04	-1.74E+00								
7.000E-04	-1.76E+00								
8.000E-04	-1.77E+00								
9.000E-04	-1.78E+00								
1.000E-03	-1.80E+00								

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

+0:1	= 1.650E+00	0:2	= -1.650E+00	0:3	= 0.
+0:4	= 0.	0:5	= 9.888E-01	0:6	= 3.715E-01
+0:7	= -5.598E-01	0:8	= -5.598E-01	0:9	= 2.916E-03
+0:10	= 2.916E-03	0:11	= -9.397E-01	0:12	= -9.397E-01
+0:13	= 0.	0:14	= 3.800E-01	0:15	= -5.600E-01
+0:16	= -6.700E-01				

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(9,10)

DC COMPONENT = -6.397D-05

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+02	7.143E-01	1.000E+00	1.764E+02	0.
2	2.000E+03	7.291E-05	1.021E-04	8.825E+01	-8.814E+01
3	3.000E+03	8.810E-06	1.233E-05	9.282E+01	-8.357E+01
4	4.000E+03	9.318E-06	1.304E-05	-8.561E+01	-2.620E+02
5	5.000E+03	1.470E-06	2.058E-06	-1.024E+02	-2.788E+02
6	6.000E+03	3.794E-06	5.312E-06	7.440E+01	-1.020E+02
7	7.000E+03	3.921E-06	5.489E-06	4.849E+00	-1.715E+02
8	8.000E+03	4.792E-06	6.708E-06	9.902E+01	-7.738E+01
9	9.000E+03	1.316E-05	1.842E-05	-1.747E+02	-3.511E+02

TOTAL HARMONIC DISTORTION = 1.058E-02 PERCENT

FULLY DIFFERENTIAL OP AMP WITH MISMATCH

```

VDD 1 0 1.65
VSS 2 0 -1.65
VI 3 4 DC 0.941468M SIN (0 1E-4 1K)
VB1 14 0 0.38
VB2 15 0 -0.56
VB3 16 0 -0.67
VCM 13 0 0
M1 7 3 5 1 CMOSF W=77.385U L=1U
M2 8 4 5 1 CMOSF W=76.615U L=1U
M3 7 15 2 2 CMOSN W=4U L=1U
M4 8 15 2 2 CMOSN W=4U L=1U
M5 5 6 1 1 CMOSF W=25U L=1U
M6 9 8 2 2 CMOSN W=16U L=1U
M7 9 14 1 1 CMOSF W=50U L=1U
M8 10 7 2 2 CMOSN W=16U L=1U
M10 10 14 1 1 CMOSF W=50U L=1U
M21 6 9 11 2 CMOSN W=8.4U L=1U
M22 1 13 11 2 CMOSN W=8.4U L=1U
M23 1 13 12 2 CMOSN W=8.4U L=1U
M24 6 10 12 2 CMOSN W=8.4U L=1U
M25 6 6 1 1 CMOSF W=25U L=1U
M26 11 16 2 2 CMOSN W=14U L=1U
M27 12 16 2 2 CMOSN W=14U L=1U
R1 3 0 1G
R2 4 0 1G
C1 7 10 1.39P
C2 8 9 1.39P
.MODEL CMOSN NMOS VTO=0.6 KP=194U TOX=8E-9 LAMBDA=0.027778 KF=3.E-24 NLEV=2
.MODEL CMOSF PMOS VTO=-0.8 KP=64.7U TOX=8E-9 LAMBDA=0.055556 KF=3.E-24 NLEV=2
.OPTIONS NOMOD
.TRAN 1U 10M
.FOUR 1K V(9, 10)
.DC VI -0.05813M, 1.94187M, 0.1M
.PLOT DC V(9, 10)
.WIDTH OUT=80
.OPTIONS SPICE
.END

```

***** DC TRANSFER CURVES THOM= 27.000 TEMP= 27.000

VOLT (A)	V(9,10)								
	-2.000E+00	-1.000E+00	0.	1.000E+00	2.000E+00				
-5.813E-05	1.80E+00								
4.187E-05	1.78E+00								
1.419E-04	1.77E+00								
2.419E-04	1.76E+00								
3.419E-04	1.74E+00								
4.419E-04	1.72E+00								
5.419E-04	1.69E+00								
6.419E-04	1.65E+00								
7.419E-04	1.42E+00								
8.419E-04	7.16E-01								
9.419E-04	-7.16E-01								
1.042E-03	-7.16E-01								
1.142E-03	-1.42E+00								
1.242E-03	-1.65E+00								
1.342E-03	-1.69E+00								
1.442E-03	-1.72E+00								
1.542E-03	-1.74E+00								
1.642E-03	-1.76E+00								
1.742E-03	-1.77E+00								
1.842E-03	-1.78E+00								
1.942E-03	-1.80E+00								

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

+0:1	= 1.650E+00	0:2	= -1.650E+00	0:3	= 0.
+0:4	= 0.	0:5	= 9.888E-01	0:6	= 3.712E-01
+0:7	= -4.401E-01	0:8	= -5.679E-01	0:9	= 4.291E-01
+0:10	= -1.364E+00	0:11	= -6.577E-01	0:12	= -1.076E+00
+0:13	= 0.	0:14	= 3.800E-01	0:15	= -5.600E-01
+0:16	= -6.700E-01				

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(9,10)

DC COMPONENT = 1.793D+00

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	9.999E+02	1.196E-02	1.000E+00	1.799E+02	0.
2	2.000E+03	3.372E-04	2.819E-02	8.962E+01	-9.030E+01
3	3.000E+03	1.324E-05	1.107E-03	-7.077E-01	-1.806E+02
4	4.000E+03	7.553E-07	6.314E-05	-8.999E+01	-2.699E+02
5	5.000E+03	6.191E-08	5.176E-06	-1.763E+02	-3.562E+02
6	6.000E+03	9.223E-08	7.710E-06	8.223E+01	-9.769E+01
7	7.000E+03	1.040E-07	8.690E-06	-4.049E+00	-1.839E+02
8	8.000E+03	8.363E-08	6.991E-06	9.101E+01	-8.891E+01
9	9.000E+03	3.080E-07	2.575E-05	1.725E+02	-7.341E+00

TOTAL HARMONIC DISTORTION = 2.821E+00 PERCENT

12-3

12.4

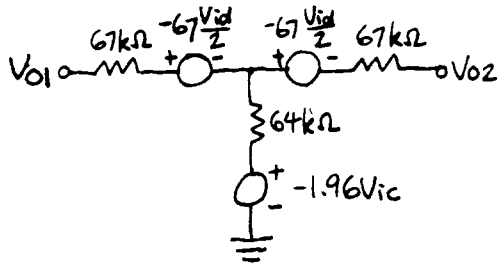
$$(a) A_{dm} = -67$$

$$\begin{aligned} \frac{R_{od}}{2} &= r_{o1} \parallel r_{o3} = \frac{V_{A1}}{I_{D1}} \parallel \frac{|V_{A3}|}{|I_{D3}|} \\ &= \frac{10}{0.1} \parallel \frac{20}{0.1} = 67 \text{ k}\Omega \end{aligned}$$

$$A_{cm} = -1.96$$

$$\begin{aligned} R_{oc} &= R_{od(own)} \parallel r_{o3} \\ &\approx [r_{o1}(g_{m1}r_{osh})] \parallel r_{o3} \\ &= \left[\frac{V_{A1}}{I_{D1}} \frac{2I_{D1}}{V_{ov1}} \frac{V_{A5h}}{I_{D5h}} \right] \parallel \frac{|V_{A3}|}{|I_{D3}|} \\ &= \left[\frac{10}{0.1} \frac{2 \times 0.1}{0.2} \frac{10}{0.1} \right] \parallel \frac{20}{0.1} \\ &= 196 \text{ k}\Omega \end{aligned}$$

$$\frac{R_{oc}}{2} - \frac{R_{od}}{4} = \frac{196}{2} - \frac{67}{2} = 64 \text{ k}\Omega$$



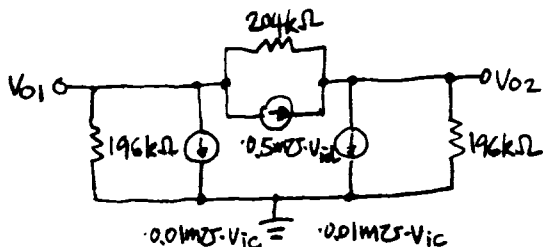
From Figs. 12.8(b) and (c),

$$G_{md} = -\frac{A_{dm}}{R_{od}} = -\frac{-67}{134} = 0.5 \text{ mA/V}$$

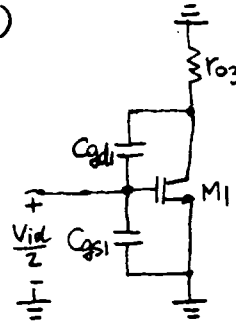
From Figs. 12.9(b) and (c),

$$G_{mc} = -\frac{A_{cm}}{R_{oc}} = -\frac{-1.96}{196} = 10^{-2} \text{ mA/V}$$

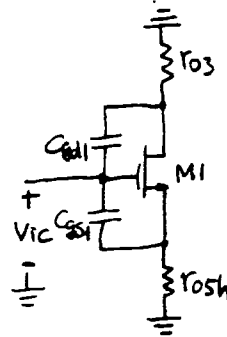
$$R_{od} \parallel (-2R_{oc}) = 134 \parallel (-392) = 204 \text{ k}\Omega$$



(b)



$$\begin{aligned} \frac{1}{2} Z_{id} &= \frac{1}{sC_{gs1}} \parallel \frac{1}{s(1-A_{dm})C_{gd1}} \\ &= \frac{1}{s[C_{gs1} + (1-A_{dm})C_{gd1}]} \end{aligned}$$



The gain from V_{ic} to the drain of M1 is $A_{cm} = -1.98$. Its contribution to Z_{ic} is

$$\frac{1}{s(1-A_{cm})C_{gd1}}$$

The gain from V_{ic} to the source of M1 is

$$a_1 = \frac{g_{m1}r_{osh}}{1+g_{m1}r_{osh}}$$

Its contribution to Z_{ic} is

$$\frac{1}{s(1-a_1)C_{gs1}} = \frac{1+g_{m1}r_{osh}}{sC_{gs1}} \approx \frac{g_{m1}r_{osh}}{sC_{gs1}}$$

$$Z_{ic} = \frac{1}{s[(1-A_{cm})C_{gd1} + \frac{1}{g_{m1}r_{osh}}C_{gs1}]}$$

12-4

$$C_{gs1} + (1 - a_{cm}) C_{gd1}$$

$$= 180 + (1 + 67) 20$$

$$= 1540 \text{ fF} = 1.5 \text{ pF}$$

$$(1 - a_{cm}) C_{gd1} + \frac{1}{g_{m1} r_{O5h}} C_{gs1}$$

$$= (1 - a_{cm}) C_{gd1} + \frac{V_{ov1} I_{D5h}}{2 I_{D1} V_{A5h}} C_{gs1}$$

$$= (1 + 1.98) 20 + \frac{0.2}{2 \times 0.1} \frac{0.1}{10} 180$$

$$= 61 \text{ fF}$$

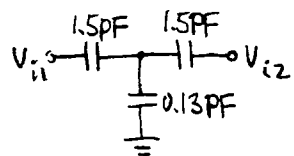
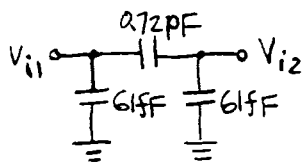
$$\frac{Z_{id}}{2} = \frac{1}{s \cdot 1.5 \text{ pF}}, \quad Z_{ic} = \frac{1}{s \cdot 61 \text{ fF}}$$

$$Z_{id} \parallel (-2Z_{ic}) = \frac{1}{s} \left(\frac{2}{1.5 \text{ pF}} \parallel \frac{-2}{61 \text{ fF}} \right)$$

$$= \frac{1}{s \cdot 0.72 \text{ pF}}$$

$$\frac{Z_{ic}}{2} - \frac{Z_{id}}{4} = \frac{1}{s} \left(\frac{1}{2 \times 61 \text{ fF}} - \frac{1}{2 \times 1.5 \text{ pF}} \right)$$

$$= \frac{1}{s \cdot 0.13 \text{ pF}}$$



12.5

$$(a) A_{dm} = -g_{m1}(r_{o1} || r_{o3}) = -\frac{2}{V_{ov1}} \frac{V_{A1} |V_{A3}|}{V_{A1} + |V_{A3}|}$$

$$= -\frac{2}{0.1} \frac{10 \times 20}{10 + 20} = -134$$

$$\frac{R_{od}}{2} = r_{o1} || r_{o3} = \frac{V_{A1}}{I_{D1}} || \frac{|V_{A3}|}{|I_{D3}|} = \frac{10}{0.05} || \frac{20}{0.05}$$

$$= 134 \text{ k}\Omega$$

$$A_{cm} = -\frac{g_{m1}}{1 + g_{m1} r_{o5h}} (R_{o(down)} || r_{o3})$$

$$\approx -\frac{1}{r_{o5h}} (R_{o(down)} || r_{o3})$$

$$\approx -\frac{1}{V_{A5h}} \frac{V_{A1} \frac{2V_{A5h}}{V_{ov1}} |V_{A3}|}{V_{A1} \frac{2V_{A5h}}{V_{ov1}} + |V_{A3}|}$$

$$= -\frac{1}{10} \frac{10 \frac{2 \times 10}{0.1} 20}{10 \frac{2 \times 10}{0.1} + 20} = -1.98$$

$$R_{oc} = R_{o(down)} || r_{o3}$$

$$\approx \left(\frac{V_{A1}}{I_{D1}} \frac{2I_{D1}}{V_{ov1}} \frac{V_{A5h}}{I_{D5h}} \right) || \frac{|V_{A3}|}{|I_{D3}|}$$

$$= \left(\frac{10}{0.05} \frac{2 \times 0.05}{0.1} \frac{10}{0.05} \right) || \frac{20}{0.05}$$

$$= 396 \text{ k}\Omega$$

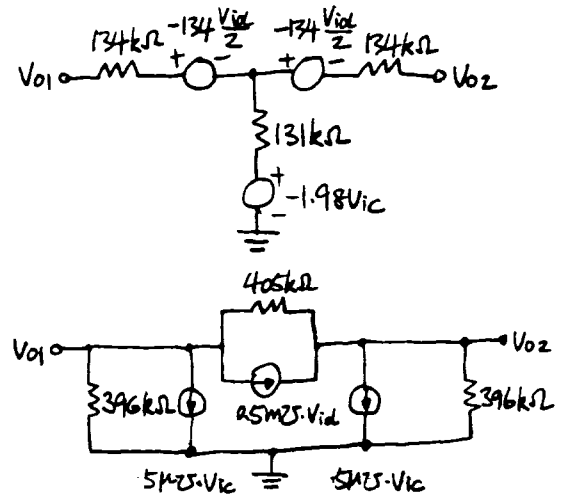
$$\frac{R_{oc}}{2} - \frac{R_{od}}{4} = \frac{396}{2} - \frac{134}{2} = 131 \text{ k}\Omega$$

$$G_{md} = -\frac{A_{dm}}{R_{od}} = -\frac{-134}{268} = 0.5 \text{ mA/V}$$

$$G_{mc} = -\frac{A_{cm}}{R_{oc}} = -\frac{-1.98}{396} = 5 \times 10^{-3} \text{ mA/V}$$

$$= 5 \mu\text{A/V}$$

$$R_{od} || (-2R_{oc}) = 268 || (-792) = 405 \text{ k}\Omega$$



(b) From 12.4,

$$C_{gs1} + (1 - A_{dm})C_{gd1}$$

$$= 180 + (1 + 134)20$$

$$= 2880 \text{ fF} = 2.9 \text{ pF}$$

$$(1 - A_{cm})C_{gd1} + \frac{1}{g_{m1} r_{o5h}} C_{gs1}$$

$$= (1 - A_{cm})C_{gd1} + \frac{V_{ov1}}{2I_{D1}} \frac{I_{D5h}}{V_{A5h}} C_{gs1}$$

$$= (1 + 1.98)20 + \frac{0.1}{2 \times 0.05} \frac{0.05}{10} 180$$

$$= 60 \text{ fF}$$

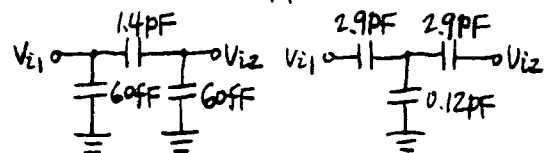
$$\frac{Z_{id}}{2} = \frac{1}{s \cdot 2.9 \text{ pF}}, Z_{ic} = \frac{1}{s \cdot 60 \text{ fF}}$$

$$Z_{id} || (-2Z_{ic}) = \frac{1}{s} \left(\frac{2}{2.9 \text{ pF}} || \frac{-2}{60 \text{ fF}} \right)$$

$$= \frac{1}{s \cdot 1.4 \text{ pF}}$$

$$\frac{Z_{ic}}{2} - \frac{Z_{id}}{4} = \frac{1}{s} \left(\frac{1}{2 \times 60 \text{ fF}} - \frac{1}{2 \times 2.9 \text{ pF}} \right)$$

$$= \frac{1}{s \cdot 0.12 \text{ pF}}$$



12-6 (b)

$$(c) a_{cmc} = -g_{msh}(R_{o\downarrow down})//r_{o3})$$

$$\approx -\frac{2}{V_{ovsh}} \frac{V_{AI} \frac{2V_{Ash}}{V_{ov1}} |V_{A3}|}{V_{AI} \frac{2V_{Ash}}{V_{ov1}} + |V_{A3}|}$$

$$= -\frac{2}{0.1} \frac{10 \frac{2 \times 10}{0.1} 20}{10 \frac{2 \times 10}{0.1} + 20}$$

$$= -396$$

12.6

$$(a) a_{cm} = -\frac{g_{mi}}{1 + g_{mi}r_{osh}} (R_{o\downarrow down})//r_{o3})$$

$$\approx -\frac{1}{r_{osh}} (R_{o\downarrow down})//r_{o3})$$

$$\approx -\frac{1}{V_{Ash}} \frac{V_{AI} \frac{2V_{Ash}}{V_{ov1}} |V_{A3}|}{V_{AI} \frac{2V_{Ash}}{V_{ov1}} + |V_{A3}|}$$

$$= -\frac{1}{10} \frac{10 \frac{2 \times 10}{0.1} 20}{10 \frac{2 \times 10}{0.1} + 20} = -1.98$$

$$a_{cmc} = -g_{msh}(R_{o\downarrow down})//r_{o3})$$

$$\approx -\frac{2}{V_{ovsh}} \frac{V_{AI} \frac{2V_{Ash}}{V_{ov1}} |V_{A3}|}{V_{AI} \frac{2V_{Ash}}{V_{ov1}} + |V_{A3}|}$$

$$= -\frac{2}{0.1} \frac{10 \frac{2 \times 10}{0.1} 20}{10 \frac{2 \times 10}{0.1} + 20} = -396$$

$$a'_{cm} = \frac{a_{cm}}{1 - a_{cms}a_{cm}} = \frac{-1.98}{1 - 1 \times (-396)}$$

$$= -5 \times 10^{-3}$$

```
OP AMP
VDD 1 0 2.5
VSS 2 0 -2.5
VI 3 0 AC 1
VB 9 0 1.7
M1 7 3 5 2 CMOSN W=57U L=0.8U
M2 8 4 5 2 CMOSN W=57U L=0.8U
M3 7 9 1 1 CMOSP W=124U L=0.8U
M4 8 9 1 1 CMOSP W=124U L=0.8U
M5 5 6 2 2 CMOSN W=113U L=0.8U
ECMC 6 0 POLY(2) (7,0) (8,0) -1.7 0.5 0.5
R1 3 0 1G
R2 4 0 1G
R12 3 4 0
.MODEL CMOSN NMOS VTO=0.7 KP=127U TOX=150E-10 LAMBDA=0.1 KP=3.E-24 NLEV=2
.MODEL CMOSP PMOS VTO=-0.7 KP=58U TOX=150E-10 LAMBDA=0.05 KP=3.E-24 NLEV=2
.OPTIONS NOMOD
.AC DEC 5 100 100MEG
.PLOT V(7) V(8)
.WIDTH OUT=80
.OPTIONS SPICE
.END
```

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

+0:1	= 2.500E+00 0:2	= -2.500E+00 0:3	= 0.
+0:4	= 0.	= -8.017E-01 0:6	= -1.701E+00
+0:7	= -1.818E-03 0:8	= -1.818E-03 0:9	= 1.700E+00

**** MOSFETS

ELEMENT	0:M1	0:M2	0:M3	0:M4	0:M5
MODEL	0:CMOSN	0:CMOSN	0:CMOSP	0:CMOSP	0:CMOSP
ID	5.057E-05	5.057E-05	-5.057E-05	-5.057E-05	1.011E-04
IBS	-1.698E-14	-1.698E-14	0.	0.	0.
IBD	-2.498E-14	-2.498E-14	2.502E-14	2.502E-14	-1.698E-14
VGS	8.017E-01	8.017E-01	-8.000E-01	-8.000E-01	7.982E-01
VDS	7.999E-01	7.999E-01	-2.501E+00	-2.501E+00	1.698E+00
VBS	-1.698E+00	-1.698E+00	0.	0.	0.
VTH	7.000E-01	7.000E-01	-7.000E-01	-7.000E-01	7.000E-01
VDSAT	1.017E-01	1.017E-01	-1.000E-01	-1.000E-01	9.818E-02
BETA	9.773E-03	9.773E-03	1.011E-02	1.011E-02	2.099E-02
GAM EFF	0.	0.	0.	0.	0.
GM	9.942E-04	9.942E-04	1.011E-03	1.011E-03	2.060E-03
GDS	4.683E-06	4.683E-06	2.247E-06	2.247E-06	8.646E-06
GMB	0.	0.	0.	0.	0.
CDTOT	1.120E-16	1.120E-16	7.618E-16	7.618E-16	4.712E-16
CGTOT	8.653E-14	8.653E-14	1.893E-13	1.893E-13	1.728E-13
CBTOT	6.998E-14	6.998E-14	1.522E-13	1.522E-13	1.387E-13
CBTOT	1.643E-14	1.643E-14	3.629E-14	3.629E-14	3.361E-14
CGS	6.998E-14	6.998E-14	1.522E-13	1.522E-13	1.387E-13
CGD	1.120E-16	1.120E-16	7.618E-16	7.618E-16	4.712E-16

***** AC ANALYSIS

THOM= 27.000 TEMP= 27.000

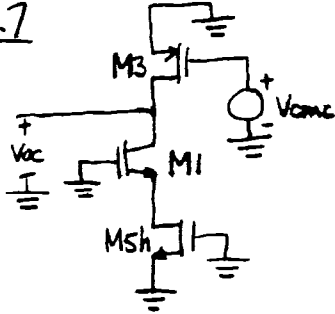
LEGEND:

A: V(7)
B: V(8)

FREQ	V(7)	V(8)	V(7)	V(8)
1.000E+02	4.178E-03	4.168E-03	4.178E-03	4.178E-03
1.584E+02	4.178E-03	4.168E-03	4.178E-03	4.178E-03
2.511E+02	4.178E-03	4.168E-03	4.178E-03	4.178E-03
3.981E+02	4.178E-03	4.168E-03	4.178E-03	4.178E-03
6.309E+02	4.178E-03	4.168E-03	4.178E-03	4.178E-03
1.000E+03	4.178E-03	4.168E-03	4.178E-03	4.178E-03
1.584E+03	4.178E-03	4.168E-03	4.178E-03	4.178E-03
2.511E+03	4.178E-03	4.168E-03	4.178E-03	4.178E-03
3.981E+03	4.178E-03	4.168E-03	4.178E-03	4.178E-03
6.309E+03	4.178E-03	4.168E-03	4.178E-03	4.178E-03
1.000E+04	4.178E-03	4.168E-03	4.178E-03	4.178E-03
1.584E+04	4.178E-03	4.168E-03	4.178E-03	4.178E-03
2.511E+04	4.178E-03	4.168E-03	4.178E-03	4.178E-03
3.981E+04	4.178E-03	4.168E-03	4.178E-03	4.178E-03
6.309E+04	4.178E-03	4.168E-03	4.178E-03	4.178E-03
1.000E+05	4.178E-03	4.168E-03	4.178E-03	4.178E-03
1.584E+05	4.178E-03	4.168E-03	4.178E-03	4.178E-03
2.511E+05	4.178E-03	4.168E-03	4.178E-03	4.178E-03
3.981E+05	4.178E-03	4.168E-03	4.178E-03	4.178E-03
6.309E+05	4.178E-03	4.168E-03	4.178E-03	4.178E-03
1.000E+06	4.178E-03	4.168E-03	4.178E-03	4.178E-03
1.584E+06	4.178E-03	4.168E-03	4.178E-03	4.178E-03
2.511E+06	4.178E-03	4.168E-03	4.178E-03	4.178E-03
3.981E+06	4.178E-03	4.168E-03	4.178E-03	4.178E-03
6.309E+06	4.178E-03	4.168E-03	4.178E-03	4.178E-03
1.000E+07	4.178E-03	4.168E-03	4.178E-03	4.178E-03
1.584E+07	4.178E-03	4.168E-03	4.178E-03	4.178E-03
2.511E+07	4.178E-03	4.168E-03	4.178E-03	4.178E-03
3.981E+07	4.178E-03	4.168E-03	4.178E-03	4.178E-03
6.309E+07	4.178E-03	4.168E-03	4.178E-03	4.178E-03
1.000E+08	4.178E-03	4.168E-03	4.178E-03	4.178E-03

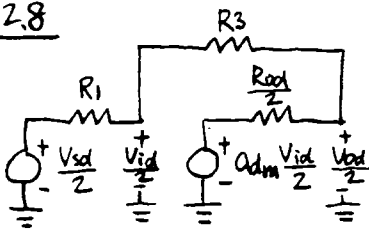
12-7

12.7



$$\begin{aligned}
 A_{cm} &= -g_{m3} (R_{odown} \parallel r_{o3}) \\
 &\approx -g_{m3} [r_{o1} (g_{m1} r_{osh}) \parallel r_{o3}] \\
 &= -\frac{2|I_{D3}|}{|V_{ov3}|} \left[\frac{V_{A1}}{I_{D1}} \frac{2I_{D1}}{V_{ov1}} \frac{V_{Ash}}{I_{Dsh}} \parallel \frac{|V_{A3}|}{|I_{D3}|} \right] \\
 &= -\frac{2}{|V_{ov3}|} \frac{V_{A1} \frac{2V_{Ash}}{V_{ov1}} |V_{A3}|}{V_{A1} \frac{2V_{Ash}}{V_{ov1}} + |V_{A3}|} \\
 &= -\frac{2}{0.1} \frac{10 \frac{2 \times 10}{0.1} 20}{10 \frac{2 \times 10}{0.1} + 20} = -396
 \end{aligned}$$

12.8

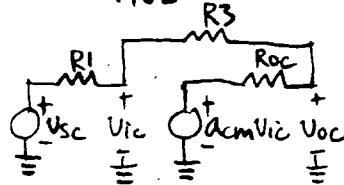


$$\begin{aligned}
 \frac{V_{id}}{2} &= A_{dm} \frac{V_{id}}{2} \frac{R_1}{R_1 + R_3 + R_{od}/2} \\
 &\quad + \frac{V_{sd}}{2} \frac{R_3 + R_{od}/2}{R_1 + R_3 + R_{od}/2} \\
 \frac{V_{id}}{2} (1 - A_{dm} \frac{R_1}{R_1 + R_3 + R_{od}/2}) &= \frac{V_{sd}}{2} \frac{R_3 + R_{od}/2}{R_1 + R_3 + R_{od}/2} \\
 \frac{V_{id}}{2} &= \frac{R_3 + R_{od}/2}{R_1 + R_3 + R_{od}/2 - A_{dm} R_1} \frac{V_{sd}}{2}
 \end{aligned}$$

$$\frac{V_{id}}{2} = \frac{V_{sd}}{2} \frac{R_3}{R_1 + R_3} + \frac{V_{sd}}{2} \frac{R_1}{R_1 + R_3}$$

$$\begin{aligned}
 V_{sd} &= \frac{R_1 + R_3}{R_1} V_{id} - \frac{R_3}{R_1} V_{sd} \\
 &= \frac{R_1 + R_3}{R_1} \frac{R_3 + R_{od}/2}{R_1 + R_3 + R_{od}/2 - A_{dm} R_1} V_{sd} \\
 &\quad - \frac{R_3}{R_1} V_{sd}
 \end{aligned}$$

$$\begin{aligned}
 A_{dm} &= \frac{R_1 + R_3}{R_1} \frac{R_3 + R_{od}/2}{R_1 + R_3 + R_{od}/2 - A_{dm} R_1} - \frac{R_3}{R_1} \\
 &= \frac{100M + 100M}{100M} \frac{100M + 134k}{100M + 100M + 134k + 134 \times 100M} \\
 &\quad - \frac{100M}{100M} \\
 &= -0.985
 \end{aligned}$$



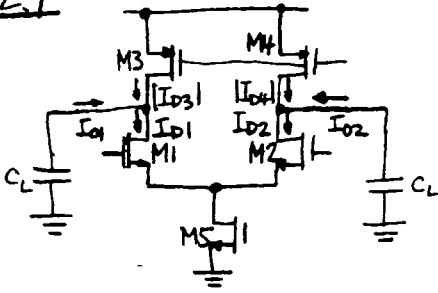
For A_{cm} , replace $R_{od}/2$ with R_{oc} , and

A_{dm} with a_{cm} ,

$$\begin{aligned}
 A_{cm} &= \frac{R_1 + R_3}{R_1} \frac{R_3 + R_{oc}}{R_1 + R_3 + R_{oc} - A_{cm} R_1} - \frac{R_3}{R_1} \\
 &= \frac{100M + 100M}{100M} \frac{100M + 396k}{100M + 100M + 396k + 1.98 \times 100M} \\
 &\quad - \frac{100M}{100M} \\
 &= -0.496
 \end{aligned}$$

12-8

12.9



$$I_{01} = I_{D1} - I_{D3}$$

$$I_{02} = I_{D2} - I_{D4}$$

$$I_{01} - I_{02} = I_{D1} - I_{D2} - (I_{D3} - I_{D4}) \\ = I_{D1} - I_{D2}$$

For I_{D1} or I_{D2} , the maximum is $200\mu A$,

$$\frac{dV_{od}}{dt} = \frac{200\mu A}{C_L} = \frac{200\mu A}{5pF} = 40V/MS$$

12.10

When M1, M2 are off,

$$\left. \frac{dV_{oc}}{dt} \right|_+ = \frac{I_{D3}}{C_L} = \frac{100\mu A}{5pF} = 20V/MS$$

When M3, M4 are off,

$$\left. \frac{dV_{oc}}{dt} \right|_- = -\frac{I_{D1}}{C_L} = -\frac{100\mu A}{5pF} = -20V/MS$$

12.11

$$\frac{dV_{od}}{dt} = \frac{I_{D5}}{C} = \frac{200\mu A}{1.39pF} = 144V/MS$$

12.12

(a)

$$|a_{cmso}| = \frac{|V_{cms}|}{|V_{oc}|} = 0.95 \frac{g_{m21}}{g_{m23}} \\ = 0.95 \frac{2k'_n(W/L)_{21}I_{D21}}{2k'_p(W/L)_{23}I_{D23}}$$

$$= 0.95 \sqrt{\frac{k'_n}{k'_p}} \sqrt{\frac{(W/L)_{21}}{(W/L)_{23}}} = 0.95 \sqrt{\frac{194}{66}} \sqrt{\frac{(W/L)_{21}}{(W/L)_{23}}} \\ = 0.71$$

Choose M23 to match M5

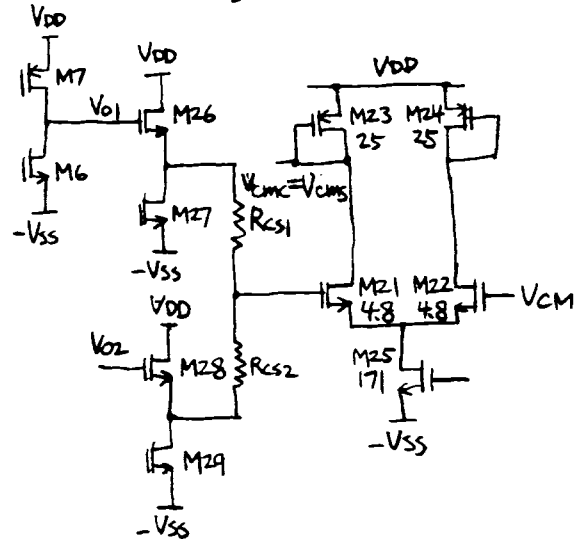
$$\therefore (W/L)_{23} = (W/L)_5 = 25$$

$$(W/L)_{21} = (W/L)_{23} \left(\frac{0.71}{0.95} \sqrt{\frac{66}{194}} \right)^2 = 4.8$$

Choose M25 to have an overdrive of $0.2V$

$$I_{D25} = 400\mu A$$

$$(W/L)_{25} = \frac{2I_{D25}}{k'_n V_{ov25}^2} = \frac{2 \times 400 \times 10^{-6}}{194 \times 10^{-6} \times 0.2^2} = 171$$



(b), (c)

$$|V_{ov7}| = \sqrt{\frac{2|I_{D7}|}{k'_p(W/L)_7}} = \sqrt{\frac{2 \times 100 \times 10^{-6}}{66 \times 10^{-6} \times 50}} = 0.25V$$

Similarly, $V_{ov6} = 0.25V$, $V_{ov21} = 0.66V$

Consider the output stage

$$-V_{SS} + V_{ov6} < V_{01} < V_{DD} - |V_{ov7}|$$

$$-1.65 + 0.25 < V_{01} < 1.65 - 0.25$$

$$-1.4V < V_{01} < 1.4V$$

Consider the source follower

$$-V_{SS} + V_{gs26} + V_{ov27} < V_{01} < V_{DD} + V_{t26}$$

$$-1.65 + 0.8 + 0.2 < V_{01} < 1.65 + 0.6$$

$$-0.65V < V_{01} < 2.25V$$

12-9

12.12 continued

Consider the CMS amplifier

$$-V_{SS} + V_{ov25} + V_{GS21} + V_{GS26} < V_{O1}$$

$$-1.65 + 0.2 + (0.6 + 0.66) + 0.8 < V_{O1}$$

$$(V_{GS21} = V_{t21} + V_{ov21})$$

$$V_{O1} > 0.61V$$

$$\therefore 0.61V < V_{O1} < 1.4V$$

To give the maximum symmetric output swing, choose the DC value of V_{O1} to be

$$\frac{1.4 + 0.61}{2} = 1V$$

$$V_{cm} = 1V - V_{GS26} = 1 - 0.8 = 0.2V$$

$$\text{The output swing is } V_{oip} = \frac{1.4 - 0.61}{2} = 0.4V$$

For the differential pair $M21, M22$ to work properly,

$$0.95 V_{oip} < \sqrt{2} V_{ov21}$$

should be satisfied.

$$0.95 V_{oip} = 0.95 \times 0.4 = 0.38V$$

$$\sqrt{2} V_{ov21} = \sqrt{2} \times 0.66 = 0.93V$$

Therefore, the CMS amplifier will be active over the entire output range.

12-10

12.12 (d)

FULLY DIFFERENTIAL OP AMP WITH CMFB

VDD 1 0 1.65
 VSS 2 0 -1.65
 VI 3 4 DC 0 SIN (0 100U 1K)
 RVCOM 30 0 POLY(2) (9, 0) (10, 0) 0 0.5 0.5
 VB1 14 0 0.38
 VB2 15 0 -0.56
 VB3 29 0 -0.85
 VCM 24 0 0.2
 M1 7 3 5 1 CMOSF W=77U L=1U
 M2 8 4 5 1 CMOSF W=77U L=1U
 M3 7 15 2 2 CMOSN W=4U L=1U
 M4 8 15 2 2 CMOSN W=4U L=1U
 M5 5 6 1 1 CMOSF W=25U L=1U
 M6 9 8 2 2 CMOSN W=16U L=1U
 M7 9 14 1 1 CMOSF W=50U L=1U
 M9 10 7 2 2 CMOSN W=16U L=1U
 M10 10 14 1 1 CMOSF W=50U L=1U
 M21 6 23 27 2 CMOSN W=4.8U L=1U
 M22 26 24 27 2 CMOSN W=4.8U L=1U
 M23 6 6 1 1 CMOSF W=25U L=1U
 M24 26 26 1 1 CMOSF W=25U L=1U
 M25 27 28 2 2 CMOSN W=96U L=1U
 VB4 28 0 -0.85
 M26 1 9 21 21 CMOSN W=14U L=1U
 M27 21 29 2 2 CMOSN W=14U L=1U
 M28 1 10 22 22 CMOSN W=14U L=1U
 M29 22 29 2 2 CMOSN W=14U L=1U
 RCS1 21 23 15K
 RCS2 22 23 15K
 R1 3 0 1G
 R2 4 0 1G
 C1 7 10 1.39P
 C2 8 9 1.39P

.MODEL CMOSN NMOS VTO=0.6 KP=194U TOX=8E-9 LAMBDA=0.027778 KP=3.E-24 NLEV=2
 .MODEL CMOSF PMOS VTO=-0.8 KP=64.7U TOX=8E-9 LAMBDA=0.055556 KP=3.E-24 NLEV=2
 .OPTIONS HOPAGE NOMOD
 .OP
 .TRAN 0.02N 1M
 .PLOT TRAN V(30)
 .WIDTH OUT=80
 .OPTIONS SPICE
 .END

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

+0:1	= 1.650E+00	0:2	= -1.650E+00	0:3	= 0.
+0:4	= 0.	0:5	= 9.882E-01	0:6	= 3.717E-01
+0:7	= -5.792E-01	0:8	= -5.792E-01	0:9	= 1.030E+00
+0:10	= 1.030E+00	0:14	= 3.800E-01	0:15	= -5.600E-01
+0:21	= 2.288E-01	0:22	= 2.288E-01	0:23	= 2.288E-01
+0:24	= 2.000E-01	0:26	= 3.928E-01	0:27	= -1.011E+00
+0:28	= -8.500E-01	0:29	= -8.500E-01	0:30	= 1.030E+00

**** MOSFETS

ELEMENT	0:M1	0:M2	0:M3	0:M4	0:M5	0:M6
MODEL	0:CMOSF	0:CMOSF	0:CMOSN	0:CMOSN	0:CMOSF	0:CMOSN
ID	-9.593E-05	-9.593E-05	9.593E-05	9.593E-05	-1.919E-04	3.696E-04
IBS	6.618E-15	6.618E-15	0.	0.	0.	0.
IBD	2.229E-14	2.229E-14	-1.071E-14	-1.071E-14	6.618E-15	-2.680E-14
VGS	-9.882E-01	-9.882E-01	1.090E+00	1.090E+00	-1.278E+00	1.070E+00
VDS	-1.567E+00	-1.567E+00	1.070E+00	1.070E+00	-6.618E-01	2.680E+00
VBS	6.618E-01	6.618E-01	0.	0.	0.	0.
VTH	-8.000E-01	-8.000E-01	6.000E-01	6.000E-01	-8.000E-01	6.000E-01
VDSAT	-1.882E-01	-1.882E-01	4.900E-01	4.900E-01	-4.783E-01	4.708E-01
BETA	5.416E-03	5.416E-03	7.991E-04	7.991E-04	1.677E-03	3.335E-03
GAM EFF	0.	0.	0.	0.	0.	0.
GM	1.019E-03	1.019E-03	3.916E-04	3.916E-04	8.022E-04	1.570E-03
GDS	4.903E-06	4.903E-06	2.588E-06	2.588E-06	1.028E-05	9.556E-06
GMB	0.	0.	0.	0.	0.	0.
CDTOT	6.946E-16	6.946E-16	2.465E-17	2.465E-17	9.522E-17	2.468E-16
CGTOT	2.516E-13	2.516E-13	1.209E-14	1.209E-14	7.560E-14	4.861E-14
CSTOT	2.216E-13	2.216E-13	1.151E-14	1.151E-14	7.194E-14	4.604E-14
CBTOT	2.929E-14	2.929E-14	5.547E-16	5.547E-16	3.562E-15	2.321E-15
CGS	2.216E-13	2.216E-13	1.151E-14	1.151E-14	7.194E-14	4.604E-14
CGD	6.946E-16	6.946E-16	2.465E-17	2.465E-17	9.522E-17	2.468E-16

ELEMENT	0:M7	0:M9	0:M10	0:M21	0:M22	0:M23
MODEL	0:CMOSF	0:CMOSN	0:CMOSF	0:CMOSN	0:CMOSN	0:CMOSF
ID	-3.696E-04	3.696E-04	-3.696E-04	1.982E-04	1.809E-04	-1.982E-04
IBS	0.	0.	0.	-6.385E-15	-6.385E-15	0.
IBD	6.200E-15	-2.680E-14	6.200E-15	-2.022E-14	-2.043E-14	1.278E-14
VGS	-1.270E+00	1.070E+00	-1.270E+00	1.240E+00	1.211E+00	-1.278E+00
VDS	-6.200E-01	2.680E+00	-6.200E-01	1.383E+00	1.404E+00	-1.278E+00
VBS	0.	0.	0.	-6.385E-01	-6.385E-01	0.
VTH	-8.000E-01	6.000E-01	-8.000E-01	6.000E-01	6.000E-01	-8.000E-01
VDSAT	-4.700E-01	4.708E-01	-4.700E-01	6.403E-01	6.115E-01	-4.783E-01
BETA	3.346E-03	3.335E-03	3.346E-03	9.670E-04	9.675E-04	1.732E-03
GAM EFF	0.	0.	0.	0.	0.	0.
GM	1.573E-03	1.570E-03	1.573E-03	6.191E-04	5.916E-04	8.287E-04
GDS	1.985E-05	9.556E-06	1.985E-05	5.302E-06	4.836E-06	1.028E-05
GMB	0.	0.	0.	0.	0.	0.
CDTOT	1.784E-16	2.468E-16	1.784E-16	3.821E-17	3.879E-17	1.839E-16
CGTOT	1.513E-13	4.861E-14	1.513E-13	1.434E-14	1.437E-14	7.569E-14
CSTOT	1.439E-13	4.604E-14	1.439E-13	1.381E-14	1.381E-14	7.194E-14
CBTOT	7.266E-15	2.321E-15	7.266E-15	4.900E-16	5.169E-16	3.562E-15
CGS	1.439E-13	4.604E-14	1.439E-13	1.381E-14	1.381E-14	7.194E-14

CGD	1.784E-16	2.468E-16	1.784E-16	3.821E-17	3.879E-17	1.839E-16
ELEMENT	0:M24	0:M25	0:M26	0:M27	0:M28	0:M29
MODEL	0:CMOSF	0:CMOSN	0:CMOSN	0:CMOSN	0:CMOSN	0:CMOSN
ID	-1.809E-04	3.791E-04	5.715E-05	5.715E-05	5.715E-05	5.715E-05
IBS	0.	0.	0.	0.	0.	0.
IBD	1.257E-14	-6.385E-15	-1.421E-14	-1.879E-14	-1.421E-14	-1.879E-14
VGS	-1.257E+00	8.000E-01	8.012E-01	8.000E-01	8.012E-01	8.000E-01
VDS	-1.257E+00	6.385E-01	1.421E+00	1.878E+00	1.421E+00	1.878E+00
VBS	0.	0.	0.	0.	0.	0.
VTH	-8.000E-01	6.000E-01	6.000E-01	6.000E-01	6.000E-01	6.000E-01
VDSAT	-4.572E-01	2.000E-01	2.012E-01	2.000E-01	2.012E-01	2.000E-01
BETA	1.730E-03	1.895E-02	2.823E-03	2.858E-03	2.823E-03	2.858E-03
GAM EFF	0.	0.	0.	0.	0.	0.
GM	7.912E-04	3.791E-03	5.681E-04	5.715E-04	5.681E-04	5.715E-04
GDS	9.393E-06	1.035E-05	1.527E-06	1.509E-06	1.527E-06	1.509E-06
GMB	0.	0.	0.	0.	0.	0.
CDTOT	1.809E-16	3.528E-16	1.145E-16	1.514E-16	1.145E-16	1.514E-16
CGTOT	7.587E-14	3.110E-13	4.539E-14	4.545E-14	4.539E-14	4.545E-14
CSTOT	7.194E-14	2.763E-13	4.029E-14	4.029E-14	4.029E-14	4.029E-14
CBTOT	3.746E-15	3.439E-14	4.985E-15	5.015E-15	4.985E-15	5.015E-15
CGS	7.194E-14	2.763E-13	4.029E-14	4.029E-14	4.029E-14	4.029E-14
CGD	1.809E-16	3.528E-16	1.145E-16	1.514E-16	1.145E-16	1.514E-16

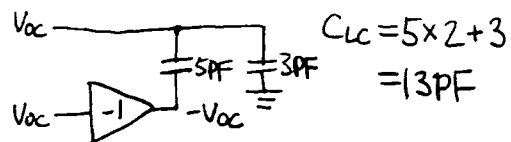
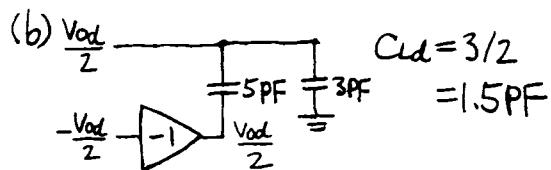
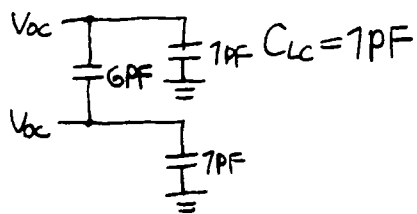
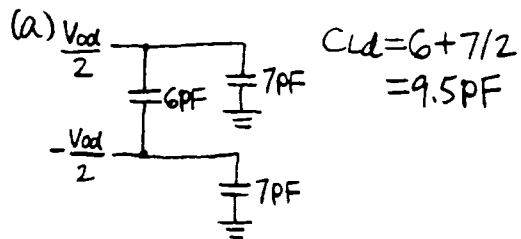
***** TRANSIENT ANALYSIS THOM= 27.000 TEMP= 27.000

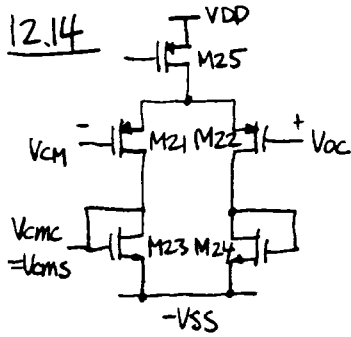
TIME	V(30)
(A)	1.028E+00
0.	1.03E+00
2.000E-05	1.03E+00
4.000E-05	1.03E+00
6.000E-05	1.03E+00
8.000E-05	1.02E+00
1.000E-04	1.02E+00
2.200E-04	1.02E+00
1.400E-04	1.02E+00
1.600E-04	1.02E+00
1.800E-04	1.02E+00
2.000E-04	1.02E+00
2.200E-04	1.02E+00
2.400E-04	1.02E+00
2.600E-04	1.02E+00
2.800E-04	1.02E+00
3.000E-04	1.02E+00
3.200E-04	1.02E+00
3.400E-04	1.02E+00
3.600E-04	1.02E+00
3.800E-04	1.02E+00
4.000E-04	1.02E+00
4.200E-04	1.02E+00
4.400E-04	1.02E+00
4.600E-04	1.03E+00
4.800E-04	1.03E+00
5.000E-04	1.03E+00
5.200E-04	1.03E+00
5.400E-04	1.03E+00
5.600E-04	1.03E+00
5.800E-04	1.02E+00
6.000E-04	1.02E+00
6.200E-04	1.02E+00
6.400E-04	1.02E+00
6.600E-04	1.02E+00
6.800E-04	1.02E+00
7.000E-04	1.02E+00
7.200E-04	1.02E+00
7.400E-04	1.02E+00
7.600E-04	1.02E+00
7.800E-04	1.02E+00
8.000E-04	1.02E+00
8.200E-04	1.02E+00
8.400E-04	1.02E+00
8.600E-04	1.02E+00
8.800E-04	1.02E+00
9.000E-04	1.02E+00
9.200E-04	1.02E+00
9.400E-04	1.02E+00
9.600E-04	1.03E+00
9.800E-04	1.03E+00
1.000E-03	1.03E+00

12-11

12.13

Symmetry or the Miller effect can be used.





$$(a) C_{ox} = \frac{\epsilon_0}{t_{ox}} = \frac{3.9 \times 8.85 \times 10^{-12}}{150 \times 10^{-10}} = 2.3 \times 10^{-3} \text{ F/m}^2$$

$$k'_n = \mu_n C_{ox} = 550 \times 10^{-4} \times 2.3 \times 10^{-3} \\ = 1.26 \times 10^{-4} \text{ A/V}^2 = 126 \mu\text{A/V}^2$$

$$\left(\frac{W}{L}\right)_{23} = \frac{2I_{D23}}{k'_n V_{ov23}^2} = \frac{2 \times 0.2 \times 10^{-3}}{126 \times 10^{-6} \times 0.2^2} = 79$$

$$W_{23} = 79 L_{eff} = 63 \mu\text{m}$$

$$C_{gs} = \frac{2}{3} W L C_{ox} + W C_{ol} \\ = \frac{2}{3} \times 63 \times 10^{-6} \times 0.8 \times 10^{-6} \times 2.3 \times 10^{-3} \\ + 63 \times 0.12 \times 10^{-15} \\ = 7.7 \times 10^{-14} + 7.6 \times 10^{-15} \\ = 8.4 \times 10^{-14} \text{ F} = 84 \text{ fF}$$

$$g_{m23} = \frac{2I_{D23}}{V_{ov23}} = \frac{2 \times 0.2 \times 10^{-3}}{0.2} = 2 \times 10^{-3} \text{ A/V}$$

The RC time constant is

$$\frac{1}{g_{m23}} (C_{gs} + 90 \text{ fF}) = \frac{1}{2 \times 10^{-3} \text{ A/V}} (84 + 90) \text{ fF} \\ = 8.7 \times 10^{-11} \text{ s} = 87 \text{ ps}$$

$$(b) \left(\frac{W}{L}\right)_{23} = 20$$

$$W = 16 \mu\text{m}$$

$$C_{gs} = 21 \text{ fF}$$

$$g_{m23} = 5 \times 10^{-4} \text{ A/V}$$

The time constant is

$$\frac{1}{5 \times 10^{-4} \text{ A/V}} (21 + 90) \text{ fF} = 2.2 \times 10^{-10} \text{ s}$$

$$= 0.22 \text{ ns}$$

(c) The size of M23 becomes $\frac{1}{4}$ the original size, hence the transconductance and gate-source capacitance, the contribution from which is the same as in the original case. The contribution from the 90 fF capacitance becomes greater, so does the total time constant.

12.15

$$(a) V_{oc} = V_{G3} = V_{DD} - |V_{tp}| - |V_{ov3}| \\ = 2.5 - 0.6 - 0.2 = 1.7 \text{ V}$$

$$(b) a_{dm} = -g_{m1} (r_{o1} \parallel r_{o3} \parallel 20 \text{ k}) \\ = -\frac{2I_{D1}}{V_{ov1}} \left(\frac{V_{A1}}{I_{D1}} \parallel \frac{|V_{A3}|}{|I_{D3}|} \parallel 20 \text{ k} \right) \\ = -\frac{2 \times 100 \times 10^{-6}}{0.2} \left(\frac{10}{100 \times 10^{-6}} \parallel \frac{20}{100 \times 10^{-6}} \parallel 20 \text{ k} \right) \\ = -1 \times 10^{-3} (100 \text{ k} \parallel 200 \text{ k} \parallel 20 \text{ k}) \\ = -15.4$$

$$a_{cm} = -\frac{g_{m1}}{1 + g_{m1} r_{osh}} (R_{odown} \parallel r_{o3}) \\ \approx -\frac{1}{r_{osh}} (R_{odown} \parallel r_{o3}) \\ = -1.96$$

In the DM half circuit, the load is $20 \text{ k}\Omega$ in parallel with $r_{o1} \parallel r_{o3}$, and is less than the original load, $r_{o1} \parallel r_{o3}$, hence the smaller DM gain. The CM circuit is not affected by the $20 \text{ k}\Omega$ resistor, so the CM gain is unchanged.

12.16

$$(a) a_{dm} = -g_{m1}(r_{o1} \parallel r_{o3}) = -66.7$$

$$a_{cm} = -g_{m1}(r_{o1} \parallel r_{o3}) = -66.7$$

(b) The DM and CM half circuits are the same as the DM half circuit in the first example in Section 12.4.1; the two gains are identical to the DM gain in that example.

12.17

$$(a) a_{dm0} = -g_{m1}(r_{o1} \parallel r_{o3})$$

$$P_{dm} = -\frac{1}{2(r_{o1} \parallel r_{o3})C_{ld}}$$

$$\begin{aligned} f_{dm,unity} &= \frac{|a_{dm0}| |P_{dm}|}{2\pi} = \frac{1}{2\pi} \frac{g_{m1}}{2C_{ld}} \\ &= \frac{1}{2\pi} \frac{1}{2C_{ld}} \frac{2I_{D1}}{V_{ov1}} \\ &= \frac{1}{2\pi} \frac{1}{2 \times 2 \times 10^{-12}} \frac{2 \times 100 \times 10^{-6}}{0.25} \\ &= 3.2 \times 10^7 \text{ Hz} = 32 \text{ MHz} \end{aligned}$$

$$a_{cm0} = -g_{msh}(R_{o(down)} \parallel r_{o3})$$

$$P_{cm} = -\frac{1}{(R_{o(down)} \parallel r_{o3})C_{LC}}$$

$$\begin{aligned} f_{cm,unity} &= \frac{|a_{cm0}| |P_{cm}|}{2\pi} = \frac{1}{2\pi} \frac{g_{msh}}{C_{LC}} \\ &= \frac{1}{2\pi} \frac{1}{C_{LC}} \frac{2I_{Dsh}}{V_{ovsh}} \\ &= \frac{1}{2\pi} \frac{1}{2 \times 10^{-12}} \frac{2 \times 100 \times 10^{-6}}{0.25} \\ &= 6.4 \times 10^7 \text{ Hz} = 64 \text{ MHz} \end{aligned}$$

$$\begin{aligned} (b) f_{dm,unity} &= \frac{1}{2\pi} \frac{1}{2C_{ld}} \frac{2I_{D1}}{V_{ov1}} \\ &= \frac{1}{2\pi} \frac{1}{2 \times 4 \times 10^{-12}} \frac{2 \times 100 \times 10^{-6}}{0.25} \\ &= 1.6 \times 10^7 \text{ Hz} = 16 \text{ MHz} \end{aligned}$$

$$\begin{aligned} f_{cm,unity} &= \frac{1}{2\pi} \frac{1}{C_{LC}} \frac{2I_{Dsh}}{V_{ovsh}} \\ &= \frac{1}{2\pi} \frac{1}{2 \times 10^{-12}} \frac{2 \times 100 \times 10^{-6}}{0.25} \\ &= 6.4 \times 10^7 \text{ Hz} = 64 \text{ MHz} \end{aligned}$$

(c) To set $f'_{cm,unity} = f_{dm,unity}$ in (a), replace M5 with M5Z

$$g_{mszh} = \frac{1}{2} g_{msh}$$

$$\frac{2I_{Dszh}}{V_{ovszh}} = \frac{1}{2} \frac{2I_{Dsh}}{V_{ovsh}}$$

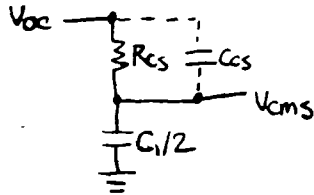
$$\begin{aligned} I_{Dszh} &= \frac{1}{2} I_{Dsh} \frac{V_{ovszh}}{V_{ovsh}} = \frac{1}{2} 100 \mu\text{A} \frac{0.25\text{V}}{0.25\text{V}} \\ &= 50 \mu\text{A} \end{aligned}$$

$$I_{D5Z} = 100 \mu\text{A}$$

$$I_{D51} = 100 \mu\text{A}$$

12-14

12.18



With $C_{CS} = 0$,

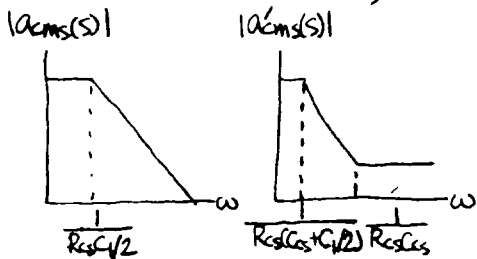
$$a_{cms}(s) = \frac{V_{cms}(s)}{V_{oc}(s)} = \frac{\frac{1}{j\omega C_L/2}}{R_{CS} + \frac{1}{j\omega C_L/2}}$$

$$= \frac{1}{1 + j\omega R_{CS} C_L/2}$$

With $C_{CS} \neq 0$,

$$a'_{cms}(s) = \frac{\frac{1}{j\omega C_L/2}}{R_{CS} \parallel \left(\frac{1}{j\omega C_{CS}} + \frac{1}{j\omega C_L/2} \right)}$$

$$= \frac{1 + j\omega R_{CS} C_{CS}}{1 + j\omega R_{CS} (C_{CS} + C_L/2)}$$



The C_{CS} capacitors introduce a LHP zero and keep $|a'_{cms}(s)|$ from dropping at high frequencies; therefore, CMFB still works at high frequencies. Also, the phase shift of $a_{cms}(s)$ approaches 0 at high frequencies.

12.19

In the triode region,

$$I_D = \frac{k'_n W}{2 L} [2(V_{GS} - V_t)V_{DS} - V_{DS}^2]$$

$$g_{m,t} = \frac{\partial I_D}{\partial V_{GS}} = \frac{k'_n W}{2 L} 2V_{DS} = k'_n \frac{W}{L} V_{DS}$$

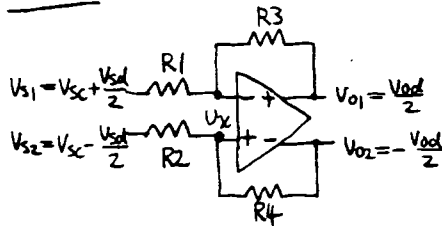
In the active region,

$$g_{m,a} = k'_n \frac{W}{L} (V_{GS} - V_t)$$

In the triode region, $V_{DS} < V_{GS} - V_t$

$$g_{m,t} < g_{m,a}$$

12.20



The opamp has infinite DM gain, so the voltages at its two inputs are the same and denoted by V_x .

It has zero CM gain, so there is no CM voltage at the outputs

$$V_{o1} = \frac{V_{od}}{2}, V_{o2} = -\frac{V_{od}}{2}$$

$$V_x = \frac{R_3}{R_1 + R_3} \left(V_{sc} + \frac{V_{sd}}{2} \right) + \frac{R_1}{R_1 + R_3} \frac{V_{od}}{2}$$

$$V_x = \frac{R_4}{R_2 + R_4} \left(V_{sc} - \frac{V_{sd}}{2} \right) - \frac{R_2}{R_2 + R_4} \frac{V_{od}}{2}$$

$$\left(\frac{R_1}{R_1 + R_3} + \frac{R_2}{R_2 + R_4} \right) \frac{V_{od}}{2}$$

$$= \left(\frac{R_4}{R_2 + R_4} - \frac{R_3}{R_1 + R_3} \right) V_{sc} - \left(\frac{R_3}{R_1 + R_3} + \frac{R_4}{R_2 + R_4} \right) \frac{V_{sd}}{2}$$

$$A_{dm} = \frac{V_{od}}{V_{sd}} = - \frac{\frac{R_3}{R_1 + R_3} + \frac{R_4}{R_2 + R_4}}{\frac{R_1}{R_1 + R_3} + \frac{R_2}{R_2 + R_4}}$$

$$A_{cm} = \frac{V_{oc}}{V_{sc}} = 0$$

$$A_{cm-dm} = \frac{V_{od}}{V_{sc}} = 2 \frac{\frac{R_4}{R_2 + R_4} - \frac{R_3}{R_1 + R_3}}{\frac{R_1}{R_1 + R_3} + \frac{R_2}{R_2 + R_4}}$$

$$A_{dm-cm} = \frac{V_{oc}}{V_{sd}} = 0$$

$$(a) A_{dm} = - \frac{\frac{5}{1+5} + \frac{5}{1+5}}{\frac{1}{1+5} + \frac{1}{1+5}} = -5$$

$$A_{cm} = 0$$

$$A_{cm-dm} = 2 \frac{\frac{5}{1+5} - \frac{5}{1+5}}{\frac{1}{1+5} + \frac{1}{1+5}} = 0$$

$$A_{dm-cm} = 0$$

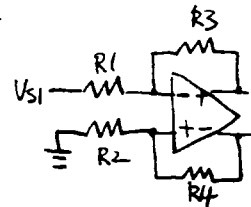
$$(b) A_{dm} = - \frac{\frac{5}{1.01+5} + \frac{5}{0.99+5}}{\frac{1.01}{1.01+5} + \frac{0.99}{0.99+5}} \approx -5$$

$$A_{cm} = 0$$

$$A_{cm-dm} = 2 \frac{\frac{5}{0.99+5} - \frac{5}{1.01+5}}{\frac{1.01}{1.01+5} + \frac{0.99}{0.99+5}} = 0.017$$

$$A_{dm-cm} = 0$$

12.21



$$V_{s1} = 0.2 \sin(100t) \text{ (V)}$$

$$V_{s2} = 0$$

$$V_{sc} = \frac{V_{s1} + V_{s2}}{2} = 0.1 \sin(100t) \text{ (V)}$$

$$V_{sd} = V_{s1} - V_{s2} = 0.2 \sin(100t) \text{ (V)}$$

$$V_{od} = A_{dm} V_{sd} + A_{cm-dm} V_{sc} = -5 \times 0.2 \sin(100t) + 0 = -1 \sin(100t) \text{ (V)}$$

$$V_{oc} = A_{cm} V_{sc} + A_{dm-cm} V_{sd} = 0$$

$$V_{o1} = V_{oc} + \frac{V_{od}}{2} = -0.5 \sin(100t) \text{ (V)}$$

$$V_{o2} = V_{oc} - \frac{V_{od}}{2} = 0.5 \sin(100t) \text{ (V)}$$

$$V_{id} = 0 \text{ (} A_{dm} = \infty \text{)}$$

$$V_{ic} = \frac{R_3}{R_1 + R_3} V_{sc} + \frac{R_1}{R_1 + R_3} V_{oc}$$

$$= \frac{5}{1+5} 0.1 \sin(100t) + \frac{1}{1+5} \cdot 0$$

$$= 0.083 \sin(100t) \text{ (V)}$$

$$V_{i1} = V_{ic} + \frac{V_{id}}{2} = 0.083 \sin(100t) \text{ (V)}$$

$$V_{i2} = V_{ic} - \frac{V_{id}}{2} = 0.083 \sin(100t) \text{ (V)}$$

12-16

12.22

$$\begin{aligned}
 (a) V_{cms} &= \frac{R_{cs2}}{R_{cs1} + R_{cs2}} V_{o1} + \frac{R_{cs1}}{R_{cs1} + R_{cs2}} V_{o2} \\
 &= \frac{R_{cs2}}{R_{cs1} + R_{cs2}} (V_{oc} + \frac{1}{2} V_{od}) + \\
 &\quad \frac{R_{cs1}}{R_{cs1} + R_{cs2}} (V_{oc} - \frac{1}{2} V_{od}) \\
 &= V_{oc} + \frac{1}{2} \frac{R_{cs2} - R_{cs1}}{R_{cs1} + R_{cs2}} V_{od}
 \end{aligned}$$

$$a_{cms} = 1$$

$$a_{dm-cms} = \frac{1}{2} \frac{R_{cs2} - R_{cs1}}{R_{cs1} + R_{cs2}} = \frac{1}{2} \frac{9.9 - 10.1}{10.1 + 9.9} = -5 \times 10^{-3}$$

$$(b) V_{od} = a_{dm} V_{id}$$

$$V_{oc} = a_{cm} V_{ic} + a_{cmc} V_{cmc}$$

$$V_{cmc} = V_{cms} = a_{cms} V_{oc} + a_{dm-cms} V_{od}$$

$$V_{oc} = a_{cm} V_{ic} + a_{cmc} a_{cms} V_{oc} +$$

$$a_{cmc} a_{dm-cms} V_{od}$$

$$= \frac{a_{cm}}{1 - a_{cmc} a_{cms}} V_{ic} + \frac{a_{cmc} a_{dm-cms}}{1 - a_{cmc} a_{cms}} a_{dm} V_{id}$$

$$\frac{V_{od}}{V_{id}} = a_{dm} = -66.7$$

$$\frac{V_{oc}}{V_{ic}} = \frac{a_{cm}}{1 - a_{cmc} a_{cms}} = \frac{-1.96}{1 - (-196)} = -1 \times 10^{-2}$$

$$\frac{V_{od}}{V_{ic}} = 0$$

$$\frac{V_{oc}}{V_{id}} = \frac{a_{cmc} a_{dm-cms}}{1 - a_{cmc} a_{cms}} a_{dm} = \frac{-196(-5 \times 10^{-3})}{1 - (-196)} (-66.7)$$

$$= -0.33$$

12.22 (c)

12-17

```

OP AMP
.SUBCKT AMP (3 4 7 8 6)
VDD 1 0 2.5
VSS 2 0 -2.5
VB 9 0 1.6
M1 7 3 5 2 CMOSN W=28.5U L=0.8U
M2 8 4 5 2 CMOSN W=28.5U L=0.8U
M3 7 9 1 1 CMOSP W=62U L=0.8U
M4 8 9 1 1 CMOSP W=62U L=0.8U
M5 5 6 2 2 CMOSN W=56.5U L=0.8U
ECMC 6 0 POLY(2) (7,0) (8,0) -1.6 0.495 0.505
R1 3 0 1G
R2 4 0 1G
.MODEL CMOSN NMOS VTO=0.7 KP=127U TOX=150E-10 LAMBDA=0.1 KP=3.E-24 NLEV=2
.MODEL CMOSP PMOS VTO=-0.7 KP=58U TOX=150E-10 LAMBDA=0.05 KP=3.E-24 NLEV=2
.ENDS AMP

* AMPLIFIER WITH DM INPUT
XDM (13 14 17 18 16) AMP
VILD 13 51 0 AC 0.5
EI2D 14 51 13 51 -1

* AMPLIFIER WITH CM INPUT
XCM (23 24 27 28 26) AMP
EI1C 23 51 13 51 2
EI2C 24 51 23 51 1

VIC 51 0 0

* AMPLIFIER WITH DM OUTPUT
XDMO (33 34 37 38 36) AMP
VOLD 37 0 0 AC 0.5
EO2D 38 0 37 0 -1

* AMPLIFIER WITH CM OUTPUT
XCMO (43 44 47 48 46) AMP
EO1C 47 0 37 0 2
EO2C 48 0 47 0 1

.OPTIONS NOMOD
* CALCULATE THE MAGNITUDE OF THE DIFFERENCES INSTEAD OF
* THE DIFFERENCE OF THE MAGNITUDES
.OPTIONS ACOUT=0
.AC DEC 1 1 10
.PRINT AC VM(17) VM(18) VP(17) VP(18)
.PRINT AC VM(27) VM(28) VP(27) VP(28)
.PRINT AC VM(17, 18) VM(17) VM(18)
.PRINT AC VM(27, 28) VM(27) VM(28)
.MEASURE AC A_DM FREQ VM(17, 18) AT=1
.MEASURE AC A_CM FREQ PAR(' (VM(27)+VM(28))/2.' ) AT=1
.MEASURE AC A_CM2DM FREQ VM(27, 28) AT=1
.MEASURE AC A_DM2CM FREQ PAR(' (VM(17)-VM(18))/2.' ) AT=1
.MEASURE AC A_CM FREQ VM(46) AT=1
.MEASURE AC A_DM2CMS FREQ VM(36) AT=1
* SUBTRACTION IS USED IN THE EQUATION FOR A_DM2CM BECAUSE
* THE TWO OUTPUTS HAVE OPPOSITE POLARITY.
.MEASURE A_DM/A_CM PARAM='A_DM/A_CM'
.MEASURE A_DM/A_CM2DM PARAM='A_DM/A_CM2DM'
.MEASURE A_DM/A_DM2CM PARAM='A_DM/A_DM2CM'
.WIDTH OUT=80
.OPTIONS SPICE
.END

***** OPERATING POINT INFORMATION          THOM= 27.000 TEMP= 27.000

+0:13      = 0.      0:14      = 0.      0:16      = -1.602E+00
+0:17      = -2.780E-03 0:18      = -2.780E-03 0:23      = 0.
+0:24      = 0.      0:26      = -1.602E+00 0:27      = -2.780E-03
+0:28      = -2.780E-03 0:33      = 0.      0:34      = 0.
+0:36      = -1.600E+00 0:37      = 0.      0:38      = 0.
+0:43      = 0.      0:44      = 0.      0:46      = -1.600E+00
+0:47      = 0.      0:48      = 0.      0:51      = 0.
+1:1       = 2.500E+00 1:2       = -2.500E+00 1:5       = -9.025E-01
+1:9       = 1.600E+00 2:1       = 2.500E+00 2:2       = -2.500E+00
+2:5       = -9.025E-01 2:9       = 1.600E+00 3:1       = 2.500E+00
+3:2       = -2.500E+00 3:5       = -9.053E-01 3:9       = 1.600E+00
+4:1       = 2.500E+00 4:2       = -2.500E+00 4:5       = -9.053E-01
+4:9       = 1.600E+00

**** MOSFETS

SUBCKT XDM XDM XDM XDM XDM XCM
ELEMENT 1:M1 1:M2 1:M3 1:M4 1:M5 2:M1
MODEL 1:CMOSN 1:CMOSN 1:CMOSP 1:CMOSP 1:CMOSN 2:CMOSN
ID 1.011E-04 1.011E-04 -1.011E-04 -1.011E-04 2.023E-04 1.011E-04
IBS -1.597E-14 -1.597E-14 0. 0. -1.597E-14
IRD -2.497E-14 -2.497E-14 2.503E-14 2.503E-14 -1.597E-14 -2.497E-14
VGS 9.025E-01 9.025E-01 -9.000E-01 -9.000E-01 8.972E-01 9.025E-01
VDS 8.998E-01 8.998E-01 -2.502E+00 -2.502E+00 1.597E+00 8.998E-01
VBS -1.597E+00 -1.597E+00 0. 0. 0. -1.597E+00
VTH 7.000E-01 7.000E-01 -7.000E-01 -7.000E-01 7.000E-01 7.000E-01
VDSAT 2.025E-01 2.025E-01 -2.000E-01 -2.000E-01 1.972E-01 2.025E-01
BETA 4.931E-03 4.931E-03 5.057E-03 5.057E-03 1.040E-02 4.931E-03
GAM EFF 0. 0. 0. 0. 0. 0.
GM 1.011E-03 1.011E-03 2.080E-03 2.080E-03 1.013E-03 1.011E-03
GDS 4.495E-06 4.495E-06 1.794E-05 1.794E-05 9.536E-06 4.495E-06
GMB 0. 0. 0. 0. 0. 0.
CITOT 3.806E-16 3.806E-16 2.212E-16 2.212E-16 6.336E-17 3.806E-16
CGTOT 8.598E-14 8.598E-14 7.823E-14 7.823E-14 3.930E-14 8.598E-14
CSTOT 7.612E-14 7.612E-14 6.937E-14 6.937E-14 3.499E-14 7.612E-14
CBTOT 9.476E-15 9.476E-15 8.635E-15 8.635E-15 4.244E-15 9.476E-15
CGS 7.612E-14 7.612E-14 6.937E-14 6.937E-14 3.499E-14 7.612E-14
CGD 3.806E-16 3.806E-16 2.212E-16 2.212E-16 6.336E-17 3.806E-16

A_DM= 7.2509E+01
A_CM= 8.3867E-03
A_CM2DM= .0000E+00
A_DM2CM= 3.6092E-01
A_CMS= 1.0000E+00
A_DM2CMS= 5.0000E-03
A_DM/A_CM= 8.6457E+03
A_DM/A_CM2DM= 7.2509E+29
A_DM/A_DM2CM= 2.0090E+02

```

12.23

$$(a) I_{DS1} = I_{D1} + I_{D2} + I_{D13} - I_{D52}$$

$$= 100 + 100 + 20 - 100 = 120 \mu A$$

$$(W/L)_{S1} = (W/L)_{14} \frac{I_{DS1}}{I_{D14}} = \frac{16}{0.8} \frac{120}{100} = \frac{19.2}{0.8}$$

$$|I_{D12}| = |I_{D13}| = 20 \mu A$$

$$(W/L)_{12} = (W/L)_{11} \frac{|I_{D12}|}{|I_{D11}|} = \frac{96}{1.4} \frac{20}{100} = \frac{19.2}{1.4}$$

$$(c) SR = \frac{dV_{out}}{dt} = 2 \frac{I_{BIAS}}{C_L} = 2 \frac{100 \mu A}{4 pF} = 50 V/\mu s$$

$$(d) \text{Use } k'_n = 1.96 \times 10^{-4} A/V^2, k'_p = 6.6 \times 10^{-5} A/V^2$$

$$V_{tn} = 0.6 V$$

$$V_{ov2} = \sqrt{\frac{2 I_D}{k'_n (W/L)}} = \sqrt{\frac{2 \times 100 \times 10^{-6}}{1.96 \times 10^{-4} \times 64 \times 0.8}} = 0.11 V$$

$$\text{Similarly, } |V_{ov4}| = 0.21 V$$

$$V_{ov13} = 0.34 V$$

$$V_{ov21} = 0.45 V$$

$$V_{omax} = V_{DD} - |V_{ov4}| = 1.65 - 0.21 = 1.44 V$$

$$V_{omin} = V_{ic} - (V_{tn} + V_{ov2}) + (V_{tn} + V_{ov13}) - V_{tn}$$

$$= V_{ic} - V_{ov2} + V_{ov13} - V_{tn}$$

$$= -0.65 - 0.11 + 0.34 - 0.6$$

$$= -1.02 V$$

$$-1.02 V < V_o < 1.44 V$$

For the CMFB to work properly,

$$V_{cm} - \sqrt{2} V_{ov21} < V_o < V_{cm} + \sqrt{2} V_{ov21}$$

$$-0.65 - \sqrt{2} 0.45 < V_o < -0.65 + \sqrt{2} 0.45$$

$$-1.29 V < V_o < -0.01 V$$

$$\therefore -1.02 V < V_o < -0.01 V$$

$$V_{o1max} = -0.65 - (-1.02) = 0.37 V$$

$$V_{admax} = 2 \times 0.37 = 0.74 V$$

12.23(b)

FULLY DIFFERENTIAL OP AMP
SUBCKT AMP (15 16 17 18)

VDD 1 0 1.65
VSS 2 0 -1.65
VCM 12 0 -0.65
IDC 14 9 -100U
M1 5 15 3 2 CMOSN W=64U L=0.8U
M2 6 16 3 2 CMOSN W=64U L=0.8U
M1C 17 4 5 2 CMOSN W=64U L=0.8U
M2C 18 4 6 2 CMOSN W=64U L=0.8U
M3 17 9 1 1 CMOSP W=96U L=1.4U
M4 18 9 1 1 CMOSP W=96U L=1.4U
M11 9 9 1 1 CMOSP W=96U L=1.4U
M12 4 9 1 1 CMOSP W=19.2U L=1.4U
M13 4 4 3 2 CMOSN W=1.4U L=0.8U
M14 14 14 2 2 CMOSN W=16U L=0.8U
M21 2 18 10 1 CMOSP W=6U L=0.8U
M22 13 12 10 1 CMOSP W=6U L=0.8U
M23 13 12 11 1 CMOSP W=6U L=0.8U
M24 2 17 11 1 CMOSP W=6U L=0.8U
M25 13 13 2 2 CMOSN W=16U L=0.8U
M26 10 9 1 1 CMOSP W=96U L=1.4U
M27 11 9 1 1 CMOSP W=96U L=1.4U
M51 3 14 2 2 CMOSN W=19.2U L=0.8U
M52 3 13 2 2 CMOSN W=16U L=0.8U

.MODEL CMOSN NMOS LEVEL=3

+ TOX=0.8000E-08 XJ=0.150000U TPG=1 PHI=0.600000
+ DELTA=2.1370E-01 LD=9.0003E-08 VTO=-0.60 GAMMA=0.5947
+ UO=450. THETA=1.9240E-01 RSH=1.7260E+01 KP=1.96E-04
+ NSUB=1.2706E+17 NPS=6.0410E+11 VMAX=1.8610E+05 ETA=2.1370E-02
+ KAPPA=8.4220E-02 CGDO=3.5E-10 CGSO=3.5E-10
+ CGBO=3.0251E-10 CJ=5.2E-04 MJ=0.59 CJSW=1.2E-10
+ MJSW=0.31 PB=0.98
+ ACM=3 HDIF=0.4U
+ .MODEL CMOSP PMOS LEVEL=3
+ TOX=0.8000E-08 XJ=0.150000U TPG=-1 PHI=0.600000
+ DELTA=2.0729E-01 LD=9.0000E-08 VTO=-0.80 GAMMA=0.5200
+ UO=137.3 THETA=1.6710E-01 RSH=3.6310E+00 KP=6.6E-05
+ NSUB=9.7132E+16 NPS=5.9890E+11 VMAX=3.0560E+05 ETA=1.8760E-02
+ KAPPA=5.9230E+00 CGDO=3.5E-10 CGSO=3.5E-10
+ CGBO=3.1661E-10 CJ=9.1191E-04 MJ=0.49 CJSW=1.2E-10
+ MJSW=0.201 PB=0.96
+ ACM=3 HDIF=0.4U
+ .ENDS AMP

* AMPLIFIER WITH DM INPUT

XDM (21 22 23 24) AMP
V11D 21 19 0 AC 0.5
E12D 22 19 21 19 -1

* AMPLIFIER WITH CM INPUT

ICM (31 32 33 34) AMP
E11C 31 19 21 19 2
E12C 32 19 31 19 1

VIC 19 0 -0.65

.OPTIONS NOMOD

* CALCULATE THE MAGNITUDE OF THE DIFFERENCES INSTEAD OF

* THE DIFFERENCE OF THE MAGNITUDES

.OPTIONS ACOUT=0

.AC DEC 1 1 10

.PRINT AC VM(23) VM(24) VP(23) VP(24)

.PRINT AC VM(33) VM(34) VP(33) VP(34)

.PRINT AC VM(23, 24) VM(23) VM(24)

.PRINT AC VM(33, 34) VM(33) VM(34)

.MEASURE AC A_DM FIND VM(23, 24) AT=1

.MEASURE AC A_CM FIND PAR('VM(33)+VM(34)')/2 AT=1

.MEASURE AC A_CM2CM FIND VM(33, 34) AT=1

.MEASURE AC A_DM2CM FIND PAR('VM(23)-VM(24)')/2 AT=1

* SUBTRACTION IS USED IN THE EQUATION FOR A_DM2CM BECAUSE

* THE TWO OUTPUTS HAVE OPPOSITE POLARITY.

.MEASURE A_DM/A_CM PARAM='A_DM/A_CM'

.MEASURE A_DM/A_CM2CM PARAM='A_DM/A_CM2CM'

.MEASURE A_DM/A_DM2CM PARAM='A_DM/A_DM2CM'

.OPTIONS SPICE

.WIDTH OUT=80

.END

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

+0:19	=-6.500E-01 0:21	=-6.500E-01 0:22	=-6.500E-01
+0:23	=-5.383E-01 0:24	=-5.383E-01 0:31	=-6.500E-01
+0:32	=-6.500E-01 0:33	=-5.383E-01 0:34	=-5.383E-01
+1:1	= 1.650E+00 1:2	=-1.650E+00 1:3	=-1.386E+00
+1:4	=-4.152E-01 1:5	=-1.190E+00 1:6	=-1.190E+00
+1:9	= 6.588E-01 1:10	= 7.433E-01 1:11	= 7.433E-01
+1:12	=-6.500E-01 1:13	=-8.566E-01 1:14	=-8.810E-01
+2:1	= 1.650E+00 2:2	=-1.650E+00 2:3	=-1.386E+00
+2:4	=-4.152E-01 2:5	=-1.190E+00 2:6	=-1.190E+00
+2:9	= 6.588E-01 2:10	= 7.433E-01 2:11	= 7.433E-01
+2:12	=-6.500E-01 2:13	=-8.566E-01 2:14	=-8.810E-01

**** MOSFETS

SUBCKT	XDM	XDM	XDM	XDM	XDM	XDM
ELEMENT	1:M1	1:M2	1:M1C	1:M2C	1:M3	1:M4

MODEL	1:CMOSH	1:CMOSH	1:CMOSH	1:CMOSH	1:CMOSP	1:CMOSP
ID	1.023E-04	1.023E-04	1.023E-04	1.023E-04	-1.023E-04	-1.023E-04
IBS	-2.636E-15	-2.636E-15	-4.594E-15	-4.594E-15	1.548E-20	1.548E-20
IBD	-4.594E-15	-4.594E-15	-1.112E-14	-1.112E-14	2.188E-14	2.188E-14
VGS	7.365E-01	7.365E-01	7.754E-01	7.754E-01	-9.912E-01	-9.912E-01
VDS	1.959E-01	1.959E-01	6.523E-01	6.523E-01	-2.188E+00	-2.188E+00
VBS	-2.635E-01	-2.635E-01	-4.594E-01	-4.594E-01	0.	0.
VTH	6.259E-01	6.259E-01	6.656E-01	6.656E-01	-7.733E-01	-7.733E-01
VDSAT	9.503E-02	9.503E-02	9.563E-02	9.563E-02	-1.875E-01	-1.875E-01
BETA	1.912E-02	1.912E-02	1.912E-02	1.912E-02	4.978E-03	4.978E-03
GAM EFF	5.270E-01	5.270E-01	5.218E-01	5.218E-01	4.909E-01	4.909E-01
GM	1.807E-03	1.807E-03	1.820E-03	1.820E-03	9.225E-04	9.225E-04
GDS	3.055E-05	3.055E-05	3.076E-05	3.076E-05	1.936E-06	1.936E-06
GMB	4.560E-04	4.560E-04	4.081E-04	4.081E-04	2.671E-04	2.671E-04
CDTOT	5.743E-14	5.743E-14	5.172E-14	5.172E-14	9.103E-14	9.103E-14
COYOT	1.592E-13	1.592E-13	1.592E-13	1.592E-13	4.046E-13	4.046E-13
CSOT	1.742E-13	1.742E-13	1.716E-13	1.716E-13	4.639E-13	4.639E-13
CSOTOT	7.279E-14	7.279E-14	6.453E-14	6.453E-14	1.511E-13	1.511E-13
CGS	1.366E-13	1.366E-13	1.366E-13	1.366E-13	3.706E-13	3.706E-13
CGD	2.240E-14	2.240E-14	2.240E-14	2.240E-14	3.360E-14	3.360E-14

SUBCKT	XDM	XDM	XDM	XDM	XDM	XDM
ELEMENT	1:M11	1:M12	1:M13	1:M14	1:M21	1:M22
MODEL	1:CMOSP	1:CMOSP	1:CMOSH	1:CMOSH	1:CMOSP	1:CMOSP
ID	-1.000E-04	-2.037E-05	2.037E-05	1.000E-04	-3.905E-05	-6.079E-05
IBS	1.513E-20	1.541E-20	-2.636E-15	-4.315E-19	9.067E-15	9.067E-15
IBD	9.912E-15	2.065E-14	-1.235E-14	-7.690E-15	3.300E-14	2.507E-14
VGS	-9.912E-01	-9.912E-01	9.712E-01	7.690E-01	-1.281E+00	-1.393E+00
VDS	-9.912E-01	-2.065E+00	9.712E-01	7.690E-01	-2.393E+00	-1.599E+00
VBS	0.	0.	-2.635E-01	0.	9.067E-01	9.067E-01
VTH	-7.756E-01	-7.737E-01	6.177E-01	5.414E-01	-9.043E-01	-9.161E-01
VDSAT	-1.855E-01	-1.870E-01	2.908E-01	1.870E-01	-3.418E-01	-4.310E-01
BETA	4.980E-03	9.56E-04	3.746E-04	4.529E-03	5.871E-04	5.749E-04
GAM EFF	4.909E-01	4.909E-01	5.270E-01	5.354E-01	4.404E-01	4.404E-01
GM	9.110E-04	1.841E-04	1.065E-04	8.345E-04	2.003E-04	2.431E-04
GDS	1.909E-06	3.862E-07	1.860E-06	1.429E-05	3.334E-06	4.291E-06
GMB	2.639E-04	5.336E-05	2.656E-05	2.527E-04	3.036E-05	3.647E-05
CDTOT	1.032E-13	1.851E-14	1.260E-15	1.370E-14	5.419E-15	5.694E-15
COYOT	4.046E-13	8.123E-14	3.665E-15	3.993E-14	1.510E-14	1.510E-14
CSOT	4.639E-13	9.293E-14	3.984E-15	4.483E-14	1.739E-14	1.739E-14
CSOTOT	1.633E-13	3.099E-14	1.954E-15	1.897E-14	8.103E-15	8.378E-15
CGS	3.706E-13	7.413E-14	2.988E-15	3.415E-14	1.280E-14	1.280E-14
CGD	3.360E-14	6.720E-15	4.900E-16	5.600E-15	2.100E-15	2.100E-15

SUBCKT	XDM	XDM	XDM	XDM	XDM	XDM
ELEMENT	1:M23	1:M24	1:M25	1:M26	1:M27	1:M51
MODEL	1:CMOSP	1:CMOSP	1:CMOSH	1:CMOSH	1:CMOSP	1:CMOSH
ID	-6.079E-05	-3.905E-05	1.216E-04	-9.984E-05	-9.984E-05	1.115E-04
IBS	9.067E-15	9.067E-15	-5.246E-19	1.510E-20	1.510E-20	-4.011E-19
IBD	2.507E-14	3.300E-14	-7.933E-15	9.067E-15	9.067E-15	-2.635E-15
VGS	-1.393E+00	-1.281E+00	7.934E-01	-9.912E-01	-9.912E-01	7.690E-01
VDS	-1.599E+00	-2.393E+00	7.934E-01	-9.067E-01	-9.067E-01	2.635E-01
VBS	9.067E-01	9.067E-01	0.	0.	0.	0.
VTH	-9.161E-01	-9.043E-01	5.409E-01	-7.758E-01	-7.758E-01	5.498E-01
VDSAT	-4.310E-01	-3.418E-01	2.065E-01	-1.853E-01	-1.853E-01	1.803E-01
BETA	5.749E-04	5.871E-04	4.800E-03	4.980E-03	4.980E-03	5.456E-03
GAM EFF	4.404E-01	4.404E-01	5.354E-01	4.909E-01	4.909E-01	5.354E-01
GM	2.431E-04	2.003E-04	9.100E-04	9.102E-04	9.102E-04	9.683E-04
GDS	4.291E-06	3.334E-06	1.563E-05	1.907E-06	1.907E-06	1.656E-05
GMB	3.647E-05	3.036E-05	2.742E-04	2.637E-04	2.637E-04	2.937E-04
CDTOT	5.694E-15	5.419E-15	1.365E-14	1.045E-13	1.045E-13	1.812E-14
COYOT	1.510E-14	1.510E-14	3.993E-14	4.046E-13	4.046E-13	4.788E-14
CSOT	1.739E-14	1.739E-14	4.483E-14	4.639E-13	4.639E-13	5.376E-14
CSOTOT	8.378E-15	8.103E-15	1.892E-14	1.645E-13	1.645E-13	2.437E-14
CGS	1.280E-14	1.280E-14	3.415E-14	3.706E-13	3.706E-13	4.098E-14
CGD	2.100E-15	2.100E-15	5.600E-15	3.360E-14	3.360E-14	6.720E-15

SUBCKT	XDM	XDM	XDM	XDM	XDM	XDM
ELEMENT	1:M52	2:M1	2:M2	2:M1C	2:M2C	2:M3
MODEL	1:CMOSH	2:CMOSH	2:CMOSH	2:CMOSH	2:CMOSH	2:CMOSP
ID	1.134E-04	1.023E-04	1.023E-04	1.023E-04	1.023E-04	1.023E-04
IBS	-4.895E-19	-2.636E-15	-2.636E-15	-4.594E-15	-4.594E-15	1.548E-20
IBD	-2.635E-15	-4.594E-15	-4.594E-15	-1.112E-14	-1.112E-14	2.188E-14
VGS	7.934E-01	7.365E-01	7.365E-01	7.754E-01	7.754E-01	-9.912E-01
VDS	2.635E-01	1.959E-01	1.959E-01	6.523E-01	6.523E-01	-2.188E+00
VBS	0.	-2.635E-01	-2.635E-01	-4.594E-01	-4.594E-01	0.
VTH	5.499E-01	6.259E-01	6.259E-01	6.656E-01	6.656E-01	-7.733E-01
VDSAT	1.995E-01	9.503E-02	9.503E-02	9.563E-02	9.563E-02	-1.875E-01
BETA	4.498E-03	1.912E-02	1.912E-02	1.912E-02	1.912E-02	4.978E-03
GAM EFF	5.354E-01	5.270E-01	5.270E-01	5.218E-01	5.218E-01	4.909E-01
GM	8.816E-04	1.807E-03	1.807E-03	1.820E-03	1.820E-03	9.225E-04
GDS	1.513E-05	3.055E-05	3.055E-05	3.076E-05	3.076E-05	1.936E-06
GMB	2.661E-04	4.560E-04	4.560E-04	4.081E-04	4.081E-04	2.671E-04
CDTOT	1.513E-14	5.743E-14	5.743E-14	5.172E-14	5.172E-14	9.103E-14
COYOT	3.993E-14	1.592E-13	1.592E-13	1.592E-13	1.592E-13	4.046E-13
CSOT	4.483E-14	1.742E-13	1.742E-13	1.716E-13	1.716E-13	4.639E-13
CSOTOT	2.040E-14	7.279E-14	7.279E-14	6.453E-14	6.453E-14	1.511E-13
CGS	3.415E-14	1.366E-13	1.366E-13	1		

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VBS	0.	0.	0.	-2.635E-01	0.	9.067E-01
VTH	-7.733E-01	-7.756E-01	-7.737E-01	6.177E-01	5.414E-01	-9.043E-01
VDSAT	-1.875E-01	-1.855E-01	-1.870E-01	2.908E-01	1.870E-01	-3.418E-01
BETA	4.978E-03	4.980E-03	9.956E-04	3.746E-04	4.529E-03	5.871E-04
GAM EFF	4.909E-01	4.909E-01	4.909E-01	5.270E-01	5.354E-01	4.404E-01
GM	9.225E-04	9.110E-04	1.841E-04	1.065E-04	8.345E-04	2.003E-04
GDS	1.936E-06	1.909E-06	3.862E-07	1.860E-06	1.429E-05	3.334E-06
GMB	2.671E-04	2.639E-04	5.336E-05	2.656E-05	2.527E-04	3.036E-05
CDTOT	9.103E-14	1.032E-13	1.851E-14	1.260E-15	1.370E-14	5.419E-15
CGTOT	4.046E-13	4.046E-13	8.123E-14	3.665E-15	3.993E-14	1.510E-14
CSTOT	4.639E-13	4.639E-13	9.293E-14	3.984E-15	4.483E-14	1.739E-14
CBTOT	1.511E-13	1.633E-13	3.099E-14	1.954E-15	1.897E-14	8.103E-15
CGS	3.706E-13	3.706E-13	7.413E-14	2.988E-15	3.415E-14	1.280E-14
CGD	3.360E-14	3.360E-14	6.720E-15	4.900E-16	5.600E-15	2.100E-15

SUBCJT	XCM	XCM	XCM	XCM	XCM	XCM
ELEMENT	2:M22	2:M23	2:M24	2:M25	2:M26	2:M27
MODEL	2:CMOSP	2:CMOSP	2:CMOSP	2:CMOSH	2:CMOSP	2:CMOSP
ID	-6.079E-05	-6.079E-05	-3.905E-05	1.216E-04	-9.984E-05	-9.984E-05
IBS	9.067E-15	9.067E-15	9.067E-15	-5.246E-19	1.510E-20	1.510E-20
IRD	2.507E-14	2.507E-14	3.300E-14	-7.933E-15	9.067E-15	9.067E-15
VGS	-1.393E+00	-1.393E+00	-1.281E+00	7.934E-01	-9.912E-01	-9.912E-01
VDS	-1.599E+00	-1.599E+00	-2.393E+00	7.934E-01	-9.067E-01	-9.067E-01
VBS	9.067E-01	9.067E-01	9.067E-01	0.	0.	0.
VTH	-9.161E-01	-9.161E-01	-9.043E-01	5.409E-01	-7.758E-01	-7.758E-01
VDSAT	-4.310E-01	-4.310E-01	-3.418E-01	2.065E-01	-1.853E-01	-1.853E-01
BETA	5.749E-04	5.749E-04	5.871E-04	4.480E-03	4.980E-03	4.980E-03
GAM EFF	4.404E-01	4.404E-01	4.404E-01	5.354E-01	4.909E-01	4.909E-01
GM	2.431E-04	2.431E-04	2.003E-04	9.100E-04	9.102E-04	9.102E-04
GDS	4.291E-06	4.291E-06	3.334E-06	1.563E-05	1.907E-06	1.907E-06
GMB	3.647E-05	3.647E-05	3.036E-05	2.742E-04	2.637E-04	2.637E-04
CDTOT	5.694E-15	5.694E-15	5.419E-15	1.365E-14	1.045E-13	1.045E-13
CGTOT	1.510E-14	1.510E-14	1.510E-14	3.993E-14	4.046E-13	4.046E-13
CSTOT	1.739E-14	1.739E-14	1.739E-14	4.483E-14	4.639E-13	4.639E-13
CBTOT	8.378E-15	8.378E-15	8.103E-15	1.892E-14	1.645E-13	1.645E-13
CGS	1.280E-14	1.280E-14	1.280E-14	3.415E-14	3.706E-13	3.706E-13
CGD	2.100E-15	2.100E-15	2.100E-15	5.600E-15	3.360E-14	3.360E-14

SUBCJT	XCM	XCM
ELEMENT	2:M51	2:M52
MODEL	2:CMOSH	2:CMOSH
ID	1.115E-04	1.134E-04
IBS	-4.011E-19	-4.895E-19
IRD	-2.635E-15	-2.635E-15
VGS	7.690E-01	7.934E-01
VDS	2.635E-01	2.635E-01
VBS	0.	0.
VTH	5.498E-01	5.499E-01
VDSAT	1.803E-01	1.995E-01
BETA	5.456E-03	4.498E-03
GAM EFF	5.354E-01	5.354E-01
GM	9.683E-04	8.816E-04
GDS	1.656E-05	1.513E-05
GMB	2.937E-04	2.661E-04
CDTOT	1.812E-14	1.513E-14
CGTOT	4.788E-14	3.993E-14
CSTOT	5.376E-14	4.483E-14
CBTOT	2.437E-14	2.040E-14
CGS	4.098E-14	3.415E-14
CGD	6.720E-15	5.600E-15

A_DM= 7.5957E+02
 A_CM= 1.2148E-01
 A_CM2DM= 4.4409E-16
 A_DM2CM= .0000E+00
 A_DM/A_CM= 6.2526E+03
 A_DM/A_CM2DM= 1.7104E+18
 A_DM/A_DM2CM= 7.5957E+30

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12.23(e)

FULLY DIFFERENTIAL OP AMP
.SUBCKT AMP (15 16 17 18)

VDD 1 0 1.65
VSS 2 0 -1.65
VCM 12 0 -0.65
IDC 14 9 -100U
M1 5 15 3 2 CMOSN W=63U L=0.8U
M2 6 16 3 2 CMOSN W=65U L=0.8U
M1C 17 4 5 2 CMOSN W=64U L=0.8U
M2C 18 4 6 2 CMOSN W=64U L=0.8U
M3 17 9 1 1 CMOSF W=96U L=1.4U
M4 18 9 1 1 CMOSF W=96U L=1.4U
M11 9 9 1 1 CMOSF W=96U L=1.4U
M12 4 9 1 1 CMOSF W=19.2U L=1.4U
M13 4 4 3 2 CMOSN W=1.4U L=0.8U
M14 14 14 2 2 CMOSN W=16U L=0.8U
M21 2 18 10 1 CMOSF W=6U L=0.8U
M22 13 12 10 1 CMOSF W=6U L=0.8U
M23 13 12 11 1 CMOSF W=6U L=0.8U
M24 2 17 11 1 CMOSF W=6U L=0.8U
M25 13 13 2 2 CMOSN W=16U L=0.8U
M26 10 9 1 1 CMOSF W=96U L=1.4U
M27 11 9 1 1 CMOSF W=96U L=1.4U
M51 3 14 2 2 CMOSN W=19.2U L=0.8U
M52 3 13 2 2 CMOSN W=16U L=0.8U

.MODEL CMOSN NMOS LEVEL=3
+ TOX=0.8000E-08 LJ=0.150000U TPG=1 PHI=0.600000
+ DELTA=2.1370E-01 LD=9.0003E-08 VTO=0.60 GAMMA=0.5947
+ UO=450. THETA=1.9240E-01 RSH=1.7260E+01 KP=1.96E-04
+ NSUB=1.2706E+17 NPS=6.0410E+11 VMAX=1.8610E+05 ETA=2.1370E-02
+ KAPPA=8.4220E-02 CGDO=3.5E-10 CGSO=3.5E-10
+ CGBO=3.0251E-10 CJ=5.2E-04 MJ=0.59 CJSW=1.2E-10
+ MJSW=0.31 PB=0.98
+ ACM=3 HDIF=0.4U
.MODEL CMOSF PMOS LEVEL=3
+ TOX=0.8000E-08 LJ=0.150000U TPG=-1 PHI=0.600000
+ DELTA=2.0729E-01 LD=9.0000E-08 VTO=-0.80 GAMMA=0.5200
+ UO=137.3 THETA=1.6710E-01 RSH=3.6310E+00 KP=6.6E-05
+ NSUB=9.7132E+16 NPS=5.9890E+11 VMAX=3.0560E+05 ETA=1.8760E-02
+ KAPPA=5.9230E+00 CGDO=3.5E-10 CGSO=3.5E-10
+ CGBO=3.1661E-10 CJ=9.1191E-04 MJ=0.49 CJSW=1.2E-10
+ MJSW=0.201 PB=0.96
+ ACM=3 HDIF=0.4U
.ENDS AMP

* AMPLIFIER WITH DM INPUT

XDM (21 22 23 24) AMP
V1D 21 19 0 AC 0.5
E12D 22 19 21 19 -1

* AMPLIFIER WITH CM INPUT

XCM (31 32 33 34) AMP
E11C 31 19 21 19 2
E12C 32 19 31 19 1

VIC 19 0 -0.65

.OPTIONS NOMOD

* CALCULATE THE MAGNITUDE OF THE DIFFERENCES INSTEAD OF

* THE DIFFERENCE OF THE MAGNITUDES

.OPTIONS ACOUT=0

.AC DEC 1 1 10

.PRINT AC VM(23) VM(24) VP(23) VP(24)

.PRINT AC VM(33) VM(34) VP(33) VP(34)

.PRINT AC VM(23, 24) VM(23) VM(24)

.PRINT AC VM(33, 34) VM(33) VM(34)

.MEASURE AC A_DM FREQ VM(23, 24) AT=1

.MEASURE AC A_CM FREQ PAR('(VM(33)+VM(34))/2.') AT=1

.MEASURE AC A_CM2DM FREQ VM(33, 34) AT=1

.MEASURE AC A_DM2CM FREQ PAR('(VM(23)-VM(24))/2.') AT=1

* SUBTRACTION IS USED IN THE EQUATION FOR A_DM2CM BECAUSE

* THE TWO OUTPUTS HAVE OPPOSITE POLARITY.

.MEASURE A_DM/A_CM PARAM='A_DM/A_CM'

.MEASURE A_DM/A_CM2DM PARAM='A_DM/A_CM2DM'

.MEASURE A_DM/A_DM2CM PARAM='A_DM/A_DM2CM'

.OPTIONS SPICE

.WIDTH OUT=80

.END

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

+0:19	=-6.500E-01 0:21	=-6.500E-01 0:22	=-6.500E-01
+0:23	= 4.319E-01 0:24	=-9.111E-01 0:31	=-6.500E-01
+0:32	=-6.500E-01 0:33	= 4.319E-01 0:34	=-9.111E-01
+1:1	= 1.650E+00 1:2	=-1.650E+00 1:3	=-1.386E+00
+1:4	=-4.148E-01 1:5	=-1.176E+00 1:6	=-1.195E+00
+1:9	= 6.588E-01 1:10	= 5.682E-01 1:11	= 8.648E-01
+1:12	=-6.500E-01 1:13	=-8.579E-01 1:14	=-8.810E-01
+2:1	= 1.650E+00 2:2	=-1.650E+00 2:3	=-1.386E+00
+2:4	=-4.148E-01 2:5	=-1.176E+00 2:6	=-1.195E+00
+2:9	= 6.588E-01 2:10	= 5.682E-01 2:11	= 8.648E-01
+2:12	=-6.500E-01 2:13	=-8.579E-01 2:14	=-8.810E-01

A_DM= 7.5617E+02
A_CM= 2.7842E-01
A_CM2DM= 2.0399E-02
A_DM2CM= 3.6278E+02

A_DM/A_CM= 2.7160E+03
A_DM/A_CM2DM= 3.7069E+04
A_DM/A_DM2CM= 2.0844E+00

12.23(f)

12-22

FULLY DIFFERENTIAL OP AMP
 .SUBCKT AMP (15 16 17 18)

A_DM/A_CM= 2.8295E+03
 A_DM/A_CM2DM= 5.2242E+04
 A_DM/A_DM2CM= -2.1714E+00

VDD 1 0 1.65
 VSS 2 0 -1.65
 VCM 12 0 -0.65
 IDC 14 9 -100U
 M1 5 15 3 2 CMOSN W=64U L=0.8U
 M2 6 16 3 2 CMOSN W=64U L=0.8U
 M1C 17 4 5 2 CMOSN W=64U L=0.8U
 M2C 18 4 6 2 CMOSN W=64U L=0.8U
 M3 17 9 1 1 CMOSP W=95U L=1.4U
 M4 18 9 1 1 CMOSP W=97U L=1.4U
 M11 9 9 1 1 CMOSP W=96U L=1.4U
 M12 4 9 1 1 CMOSP W=19.2U L=1.4U
 M13 4 4 3 2 CMOSN W=1.4U L=0.8U
 M14 14 14 2 2 CMOSN W=16U L=0.8U
 M21 2 18 10 1 CMOSP W=6U L=0.8U
 M22 13 12 10 1 CMOSP W=6U L=0.8U
 M23 13 12 11 1 CMOSP W=6U L=0.8U
 M24 2 17 11 1 CMOSP W=6U L=0.8U
 M25 13 13 2 2 CMOSN W=16U L=0.8U
 M26 10 9 1 1 CMOSP W=96U L=1.4U
 M27 11 9 1 1 CMOSP W=96U L=1.4U
 M51 3 14 2 2 CMOSN W=19.2U L=0.8U
 M52 3 13 2 2 CMOSN W=16U L=0.8U
 .MODEL CMOSN NMOS LEVEL=3
 + TOX=0.8000E-08 XJ=0.150000U TPG=1 PHI=0.600000
 + DELTA=2.1370E-01 LD=9.0003E-08 VTO=0.60 GAMMA=0.5947
 + UO=450. THETA=1.9240E-01 RSH=1.7260E+01 KP=1.96E-04
 + NSUB=1.2706E+17 NPS=5.0410E+11 VMAX=1.8610E+05 ETA=2.1370E-02
 + KAPPA=8.4220E-02 CGDO=3.5E-10 CGSO=3.5E-10
 + CGBO=3.0251E-10 CJ=5.2E-04 MJ=0.59 CJSW=1.2E-10
 + MJTSM=0.31 PB=0.98
 + ACM=3 HDIF=0.4U
 .MODEL CMOSP PMOS LEVEL=3
 + TOX=0.8000E-08 XJ=0.150000U TPG=-1 PHI=0.600000
 + DELTA=2.0729E-01 LD=9.0000E-08 VTO=-0.80 GAMMA=0.5200
 + UO=137.3 THETA=1.6710E-01 RSH=3.6310E+00 KP=6.6E-05
 + NSUB=9.7132E+16 NPS=5.9890E+11 VMAX=3.0560E+05 ETA=1.8760E-02
 + KAPPA=5.9230E+00 CGDO=3.5E-10 CGSO=3.5E-10
 + CGBO=3.1661E-10 CJ=9.1191E-04 MJ=0.49 CJSW=1.2E-10
 + MJTSM=0.201 PB=0.96
 + ACM=3 HDIF=0.4U
 .ENDS AMP

* AMPLIFIER WITH DM INPUT

XDM (21 22 23 24) AMP
 V1D 21 19 0 AC 0.5
 R1ZD 22 19 21 19 -1

* AMPLIFIER WITH CM INPUT

XCM (31 32 33 34) AMP
 R11C 31 19 21 19 2
 R12C 32 19 31 19 1

VIC 19 0 -0.65

.OPTIONS NOMOD

* CALCULATE THE MAGNITUDE OF THE DIFFERENCES INSTEAD OF

* THE DIFFERENCE OF THE MAGNITUDES

.OPTIONS ACOUT=0

.AC DEC 1 1 10

.PRINT AC VM(23) VM(24) VP(23) VP(24)

.PRINT AC VM(33) VM(34) VP(33) VP(34)

.PRINT AC VM(23, 24) VM(23) VM(24)

.PRINT AC VM(33, 34) VM(33) VM(34)

.MEASURE AC A_DM FIND VM(23, 24) AT=1

.MEASURE AC A_CM FIND PAR('(VM(33)+VM(34))/2.') AT=1

.MEASURE AC A_CM2DM FIND VM(33, 34) AT=1

.MEASURE AC A_DM2CM FIND PAR('(VM(23)-VM(24))/2.') AT=1

* SUBTRACTION IS USED IN THE EQUATION FOR A_DM2CM BECAUSE

* THE TWO OUTPUTS HAVE OPPOSITE POLARITY.

.MEASURE A_DM/A_CM PARAM='A_DM/A_CM'

.MEASURE A_DM/A_CM2DM PARAM='A_DM/A_CM2DM'

.MEASURE A_DM/A_DM2CM PARAM='A_DM/A_DM2CM'

.OPTIONS SPICE

.WIDTH OUT=80

.END

***** OPERATING POINT INFORMATION THOM= 27.000 TEMP= 27.000

+0:19	=-6.500E-01 0:21	=-6.500E-01 0:22	=-6.500E-01
+0:23	=-9.018E-01 0:24	= 5.783E-03 0:31	=-6.500E-01
+0:32	=-6.500E-01 0:33	=-9.018E-01 0:34	= 5.783E-03
+1:1	= 1.650E+00 1:2	=-1.650E+00 1:3	=-1.386E+00
+1:4	=-4.151E-01 1:5	=-1.195E+00 1:6	=-1.183E+00
+1:9	= 6.588E-01 1:10	= 8.646E-01 1:11	= 5.734E-01
+1:12	=-6.500E-01 1:13	=-8.570E-01 1:14	=-8.810E-01
+2:1	= 1.650E+00 2:2	=-1.650E+00 2:3	=-1.386E+00
+2:4	=-4.151E-01 2:5	=-1.195E+00 2:6	=-1.183E+00
+2:9	= 6.588E-01 2:10	= 8.646E-01 2:11	= 5.734E-01
+2:12	=-6.500E-01 2:13	=-8.570E-01 2:14	=-8.810E-01

A_DM= 7.5724E+02
 A_CM= 2.6762E-01
 A_CM2DM= 1.4495E-02
 A_DM2CM= -3.4873E+02

12-23

12.24

$$(a) C_{ld} = \frac{1}{2} \left(0.5 + \frac{1.5 \times 1}{1.5 + 1} \right) = 0.55 \text{ pF}$$

$$C_{lc} = 0.5 + \frac{1.5 \times 1}{1.5 + 1} = 1.1 \text{ pF}$$

$$(b) \frac{dV_{out}}{dt} = \frac{2|I_{D1}|}{2C_{ld}} = \frac{200 \mu\text{A}}{1.1 \text{ pF}} = 182 \text{ V}/\mu\text{s}$$

$$(c) -V_{SS} + V_{OV11} + V_{OV1A} < V_{O1} < V_{DD} - |V_{OV3}| - |V_{OV3A}|$$

$$-2 + 0.15 + 0.15 < V_{O1} < 2 - 0.15 - 0.15$$

$$-1.7 \text{ V} < V_{O1} < 1.7 \text{ V}$$

$$V_{od(\text{peak})} = 1.7 - (-1.7) = 3.4 \text{ V}$$

12.25

$$(a) V_{CM} - V_{OC} = V_{CBIAS} - V_{cmc}$$

$$0.5 - 0.5 = -1 - V_{cmc}$$

$$V_{cmc} = -1 \text{ V}$$

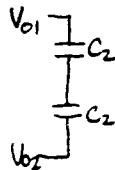
$$V_{CM} - V'_{OC} = V'_{CBIAS} - V_{cmc}$$

$$0.5 - V'_{OC} = -1.1 - (-1)$$

$$V'_{OC} = 0.6 \text{ V}$$

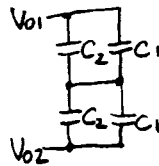
$$(b) C_{lc} = 0$$

$$C_{ld} = \frac{1}{2} C_2 = 0.25 \text{ pF}$$



$$(c) C_{lc} = 0$$

$$C_{ld} = \frac{1}{2} (C_1 + C_2) = 0.3 \text{ pF}$$



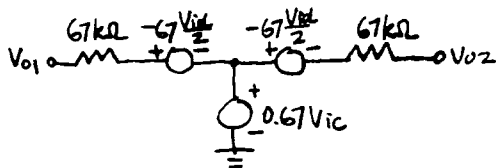
12.26

$$\begin{aligned}
 (a) A_{dm} &= -\frac{g_{m1}}{g_{m3}} g_{m8} (r_{o8} \parallel r_{o9}) \\
 &= -\frac{2I_{D1}}{V_{ov1}} \frac{|V_{ov3}|}{2|I_{D3}|} \frac{2|I_{D8}|}{|V_{ov8}|} \left(\frac{|V_{A8}|}{|I_{D8}|} \parallel \frac{V_{A9}}{I_{D9}} \right) \\
 &= -\frac{2}{0.2} (20 \parallel 10) = -67
 \end{aligned}$$

$$\begin{aligned}
 \frac{R_{od}}{2} &= r_{o8} \parallel r_{o9} = \frac{|V_{A8}|}{|I_{D8}|} \parallel \frac{V_{A9}}{I_{D9}} \\
 &= \frac{20}{100 \times 10^{-6}} \parallel \frac{10}{100 \times 10^{-6}} = 6.7 \times 10^4 \Omega = 67 \text{ k}\Omega
 \end{aligned}$$

$$\begin{aligned}
 A_{cm} &= \frac{g_{m1}}{1 + g_{m1} r_{o5h}} \frac{1}{g_{m3}} g_{m8} (r_{o8} \parallel r_{o9}) \\
 &\approx \frac{1}{r_{o5h}} \frac{g_{m8}}{g_{m3}} (r_{o8} \parallel r_{o9}) \\
 &= \frac{I_{D5h}}{V_{A5h}} \frac{|V_{ov3}|}{2|I_{D3}|} \frac{2|I_{D8}|}{|V_{ov8}|} \left(\frac{|V_{A8}|}{|I_{D8}|} \parallel \frac{V_{A9}}{I_{D9}} \right) \\
 &= \frac{1}{10} (20 \parallel 10) = 0.67
 \end{aligned}$$

$$R_{ac} = \frac{R_{od}}{2} = 67 \text{ k}\Omega$$



$$\begin{aligned}
 (b) A_{cmc} &= g_{m5h} [R_{od(own)} \parallel \frac{1}{g_{m3}}] g_{m8} (r_{o8} \parallel r_{o9}) \\
 &\approx \frac{g_{m5h}}{g_{m3}} g_{m8} (r_{o8} \parallel r_{o9}) \\
 &= \frac{2I_{D5h}}{V_{ov5h}} \frac{|V_{ov3}|}{2|I_{D3}|} \frac{2|I_{D8}|}{|V_{ov8}|} \left(\frac{|V_{A8}|}{|I_{D8}|} \parallel \frac{V_{A9}}{I_{D9}} \right) \\
 &= \frac{2}{0.2} (20 \parallel 10) = 67
 \end{aligned}$$

$$\begin{aligned}
 (c) A_{cmc} &= -g_{m9} (r_{o8} \parallel r_{o9}) \\
 &= -\frac{2I_{D9}}{V_{ov9}} \left(\frac{|V_{A8}|}{|I_{D8}|} \parallel \frac{V_{A9}}{I_{D9}} \right) \\
 &= -\frac{2}{0.2} (20 \parallel 10) = -67
 \end{aligned}$$

$$\begin{aligned}
 (d) -V_{SS} + V_{ov7} &< V_{O1} < V_{DD} - |V_{ov6}| \\
 -1.65 + 0.2 &< V_{O1} < 1.65 - 0.2 \\
 -1.45 \text{ V} &< V_{O1} < 1.45 \text{ V}
 \end{aligned}$$

If $V_{oc} = 0\text{V}$, the maximum symmetric output swing (2.9V peak to peak) can be achieved.

12-25

12.27

$$V_{oc} = a_{cm} V_{ic} + a_{cmc} V_{cmc}$$

$$= a_{cm} V_{ic} + a_{cmc} a_{cms} V_{oc}$$

$$a'_{cm} = \frac{V_{oc}}{V_{ic}} = \frac{a_{cm}}{1 - a_{cmc} a_{cms}}$$

$$V_{An} = \frac{L_{eff}}{dX_d/dV_{ds}} = \frac{1 - 2 \times 0.09}{0.02} = 41V$$

$$|V_{Ap}| = \frac{L_{eff}}{dX_d/dV_{ds}} = \frac{1 - 2 \times 0.09}{0.04} = 20.5V$$

$$a_{cm} = \frac{V_{oc}}{V_{ic}} \bigg|_{V_{cmc}=0}$$

$$= \frac{g_{m2}}{1 + g_{m2} r_{osh}} [R_{o(down)} \parallel r_{o4}] g_{m6} (r_{o6} \parallel r_{o7})$$

$$\approx \frac{1}{r_{osh}} [(r_{o2} g_{m2} r_{osh}) \parallel r_{o4}] g_{m6} (r_{o6} \parallel r_{o7})$$

$$= \frac{|I_{DSh}|}{|V_{ASh}|} \left[\left(\frac{|V_{A2}|}{|I_{D2}|} \frac{2}{|V_{ov2}|} \frac{|V_{ASh}|}{|I_{DSh}|} \right) \parallel \frac{|V_{A4}|}{|I_{D4}|} \right] \times$$

$$\frac{2I_{D6}}{V_{ov6}} \left(\frac{V_{A6}}{I_{D6}} \parallel \frac{|V_{A7}|}{|I_{D7}|} \right)$$

$$= \frac{100}{20.5} \left[\left(\frac{20.5}{100} \frac{2 \times 100}{0.2} \frac{20.5}{100} \right) \parallel \frac{41}{100} \right] \times$$

$$\frac{2 \times 400}{0.5} \left(\frac{41}{400} \parallel \frac{20.5}{400} \right)$$

$$= 108$$

$$a_{cmc} = \frac{V_{oc}}{V_{cmc}} \bigg|_{V_{ic}=0}$$

$$= g_{mSh} [(r_{o2} g_{m2} r_{osh}) \parallel r_{o4}] g_{m6} (r_{o6} \parallel r_{o7})$$

$$= \frac{2|I_{DSh}|}{|V_{ovSh}|} [(r_{o2} g_{m2} r_{osh}) \parallel r_{o4}] g_{m6} (r_{o6} \parallel r_{o7})$$

$$= \frac{2 \times 100}{0.5} \times 2.22 \times 10^3$$

$$= 8.88 \times 10^3$$

$$a_{cms} = \frac{V_{cms}}{V_{oc}} = \frac{V_{cmc}}{V_{oc}} = -\frac{g_{m21}}{g_{m25}} = -\frac{2I_{D21}}{V_{ov21}} \frac{|V_{ov25}|}{2|I_{D25}|}$$

$$= -\frac{2 \times 100}{0.35} \frac{0.5}{2 \times 200} = -0.71$$

$$a'_{cm} = \frac{108}{1 - 8.88 \times 10^3 (-0.71)} = 0.0171$$

12.28

For the CMC loop,

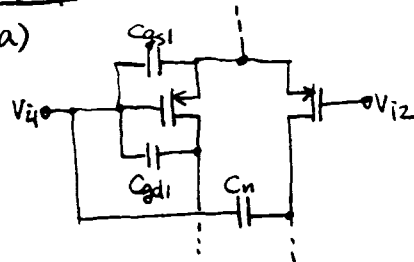
$$C = \frac{g_{mSh}}{g_{m6}} |a_{cms}| C_{zc}$$

$$= \frac{2 \times 100 \times 10^6}{0.5} \frac{1}{1.55 \times 10^{-3}} 2.5 \times 343 \times 10^{-12}$$

$$= 2.22 \times 10^{-12} F = 2.22 pF$$

For the DM loop, $C = 1.39 pF$ according to the example.Choose the larger one, that is, $C = 2.22 pF$.12.29

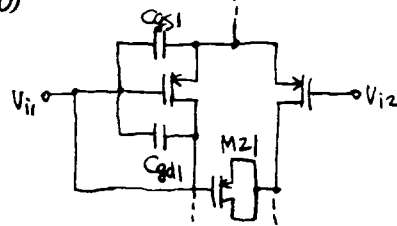
(a)

If $C_n = C_{gd1}$,

$$C_{idn} = C_{gs1} + (1 - a_{dm}) C_{gd1} + (1 + a_{dm}) C_n$$

$$= C_{gs1} + 2C_{gd1}$$

(b)

The transistor, M_{21} , should be PMOS.

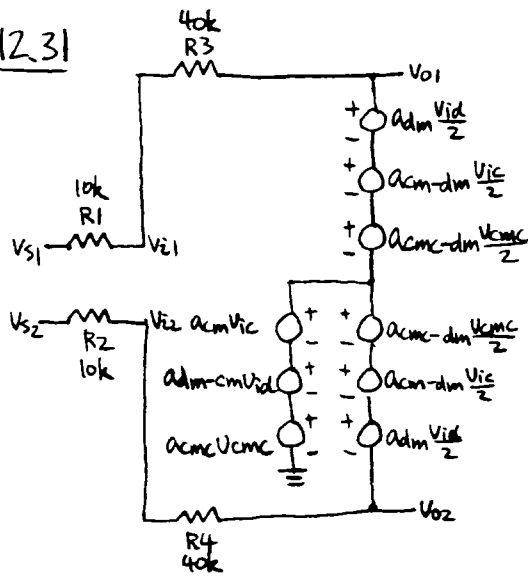
$$W_{21} = W_1/2$$

$$C_{gd1} = C_{ol} W_1$$

$$C_n = C_{gd21} + C_{gs21} = 2C_{ol} W_{21}$$

$$C_n = C_{gd1}$$

12.31



$$V_{cm} = V_{cm_s} = A_{cm_s} V_{sc}$$

$$= A_{cm_s} (A_{cm} V_{ic} + A_{dm-cm} V_{id} + A_{cm-c} V_{cm})$$

$$V_{cm} = \frac{A_{cm_s}}{1 - A_{cm_s} A_{cm}} (A_{cm} V_{ic} + A_{dm-cm} V_{id})$$

$$= \frac{0.76}{1 - 0.76 \times (-226)} (-2.89 V_{ic} + 8.95 V_{id})$$

$$= -0.0127 V_{ic} + 0.0394 V_{id}$$

$$\frac{1}{2} V_{id} = \frac{R_3}{R_1 + R_3} \frac{V_{sd}}{2} +$$

$$\frac{R_1}{R_1 + R_3} [A_{dm} \frac{V_{id}}{2} + A_{cm-dm} \frac{V_{ic}}{2} + A_{cm-c-dm} \frac{V_{cm}}{2}]$$

$$V_{id} = \frac{4}{5} V_{sd} + \frac{1}{5} [-181 V_{id} + 0.15 V_{ic} + 11.6 (-0.0127 V_{ic} + 0.0394 V_{id})]$$

$$37.1 V_{id} - 5.36 \times 10^{-4} V_{ic} = 0.8 V_{sd}$$

$$V_{ic} = \frac{R_3}{R_1 + R_3} V_{sc}$$

$$+ \frac{R_1}{R_1 + R_3} [A_{cm} V_{ic} + A_{dm-cm} V_{id} + A_{cm-c} V_{cm}]$$

$$V_{ic} = \frac{4}{5} V_{sc} + \frac{1}{5} [-2.89 V_{ic} + 8.95 V_{id} - 226 (-0.0127 V_{ic} + 0.0394 V_{id})]$$

$$V_{ic} - 9.12 \times 10^{-3} V_{id} = 0.8 V_{sc}$$

$$\begin{cases} 37.1 V_{id} - 5.36 \times 10^{-4} V_{ic} = 0.8 V_{sd} \\ -9.12 \times 10^{-3} V_{id} + V_{ic} = 0.8 V_{sc} \end{cases}$$

$$\begin{cases} 37.1 V_{id} - 5.36 \times 10^{-4} V_{ic} = 0.8 V_{sd} \\ -9.12 \times 10^{-3} V_{id} + V_{ic} = 0.8 V_{sc} \end{cases}$$

12-27

$$V_{id} = \frac{1}{37.1} (0.8 V_{sd} + 5.36 \times 10^{-4} \times 0.8 V_{sc})$$

$$= 0.0216 V_{sd} + 1.16 \times 10^{-5} V_{sc}$$

$$V_{ic} = \frac{1}{37.1} (37.1 \times 0.8 V_{sc} + 9.12 \times 10^{-3} \times 0.8 V_{sd})$$

$$= 1.97 \times 10^{-4} V_{sd} + 0.8 V_{sc}$$

$$V_{od} = A_{dm} V_{id} + A_{cm-dm} V_{ic} + A_{cm-c-dm} V_{cm}$$

$$= (A_{dm} + 0.0394 A_{cm-c-dm}) V_{id}$$

$$+ (A_{cm-dm} - 0.0127 A_{cm-c-dm}) V_{ic}$$

$$= (-181 + 0.0394 \times 11.6) V_{id}$$

$$+ (0.15 - 0.0127 \times 11.6) V_{ic}$$

$$= -180 V_{id} + 2.68 \times 10^{-3} V_{ic}$$

$$= -180 (0.0216 V_{sd} + 1.16 \times 10^{-5} V_{sc})$$

$$+ 2.68 \times 10^{-3} (1.97 \times 10^{-4} V_{sd} + 0.8 V_{sc})$$

$$= -3.89 V_{sd} + 5.6 \times 10^{-5} V_{sc}$$

$$V_{oc} = A_{cm} V_{ic} + A_{dm-cm} V_{id} + A_{cm-c} V_{cm}$$

$$= (A_{cm} - 0.0127 A_{cm-c}) V_{ic}$$

$$+ (A_{dm-cm} + 0.0394 A_{cm-c}) V_{id}$$

$$= [-2.89 - 0.0127 \times (-226)] V_{ic}$$

$$+ [8.95 + 0.0394 \times (-226)] V_{id}$$

$$= -0.0198 V_{ic} + 0.0456 V_{id}$$

$$= -0.0198 (1.97 \times 10^{-4} V_{sd} + 0.8 V_{sc})$$

$$+ 0.0456 (0.0216 V_{sd} + 1.16 \times 10^{-5} V_{sc})$$

$$= 9.81 \times 10^{-4} V_{sd} - 0.0158 V_{sc}$$

$$A_{dm} = \frac{V_{od}}{V_{sd}} = -3.89$$

$$A_{cm} = \frac{V_{oc}}{V_{sc}} = -0.0158$$

$$A_{dm-cm} = \frac{V_{oc}}{V_{sd}} = 9.81 \times 10^{-4}$$

$$A_{cm-dm} = \frac{V_{od}}{V_{sc}} = 5.6 \times 10^{-5}$$